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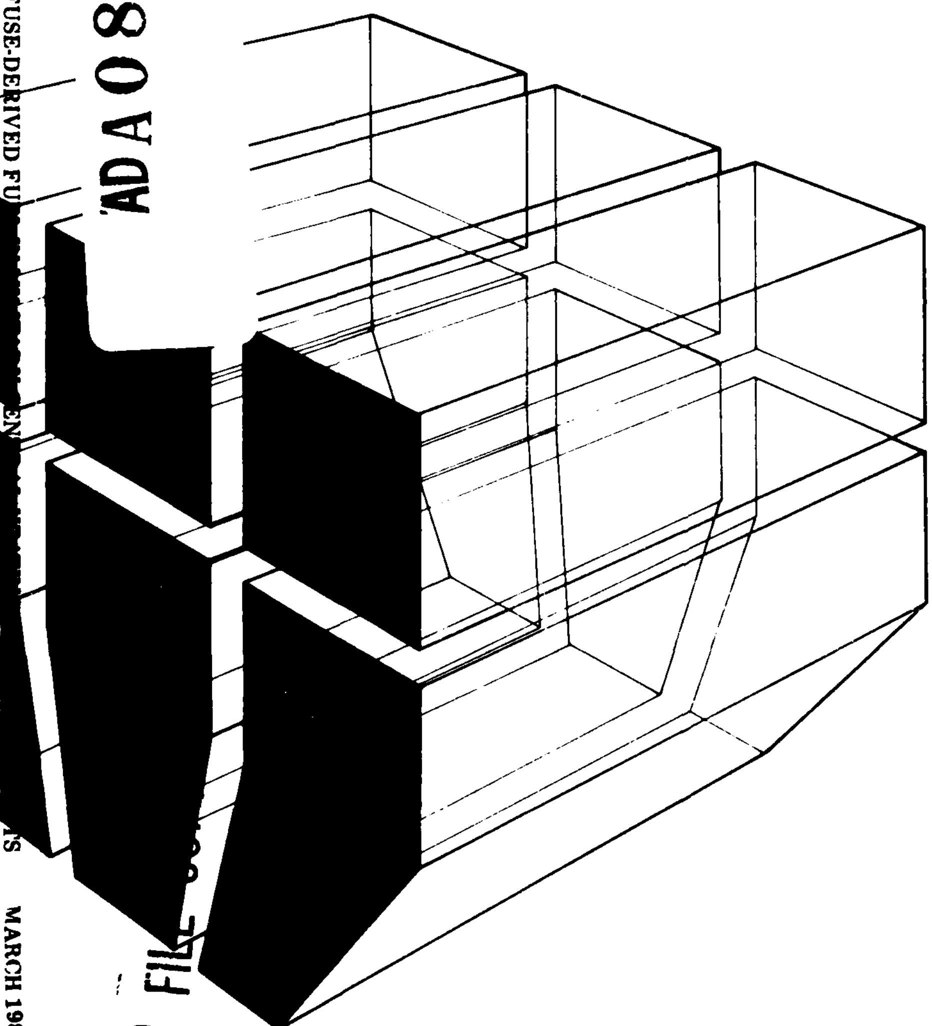
TECHNICAL REPORT E-159
March 1980

PRODUCTION AND USE OF DENSIFIED REFUSE-DERIVED FUEL (DRDF) IN MILITARY CENTRAL HEATING AND POWER PLANTS



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This investigation was sponsored by the U.S. Air Force to appraise the state of the art of production and use of densified refuse-derived fuel (DRDF) in military-scale (25 to 200 MBtu per hour) central heating and power plants. This assessment is based on critical review of scientific and engineering research, development, test, and evaluation (RDT&E), and analysis of refuse-processing facilities.

The study found that few performance and economic data exist for military-scale DRDF production unit operations. Although theoretical modeling of some operations

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(shredding, air classifying, pelleting) is generally well developed, field verification of the models is beleaguered by continued alterations of in-place equipment design to improve performance, lack of a uniform method to characterize refuse input to processes, and absence of an industry-wide commitment to monitor equipment performance. Although

They

Nearly two dozen DRDF tests have been conducted by industry and the armed services. Characteristically, these tests have been short-term experiments that have not followed the scientific method and have been inconclusive regarding long-term DRDF use in military heating and power plants. This study found that such experiments have emphasized testing the variety of DRDF products promoted on the free market, rather than following traditional fuel substitution strategies by first assessing critical plant design parameters and then determining and procuring the optimal DRDF product for use. It was also found that uniform procedures for determining many essential fuel properties of DRDF do not exist. As a result, proper and realistic specification of DRDF for military procurement cannot be made.

The study also found that lack of operating data, standard analytical procedures, and experience in military-scale DRDF systems engenders high risk in their implementation at present. Risks include potential inability to meet long-term contractual obligations to civilian producers-suppliers for DRDF procurement, and possible sacrifice of heating and power plants' readiness to operate reliably at or above design maximum continuous rating under mobilization conditions.

The study found that proper management and disposal of byproducts and potential environmental pollutants from DRDF production and use can be achieved with available technology, but that the costs of control are significant.

The study recommends a priority multiyear resource commitment by the armed services both to conduct laboratory investigations into user-oriented problems of DRDF use (storage, handling, combustion, fuel specification) and to design and conduct a well-hypothesized and thoroughly instrumented DRDF demonstration for a year or more at a selected military installation.

FOREWORD

The U.S. Army Construction Engineering Research Laboratory (CERL) conducted this study for the Air Force Engineering and Services Center (AFESC) under MIPR FY8952-78-65012, dated 24 May 1978. The Air Force Project Officer was MAJ R. F. Olfenbuttel (AFESC/RDVW, Tyndall Air Force Base, FL). The CERL Principal Investigator was Mr. S. Hathaway of the Energy and Habitability Division (CERL-EH).

Appreciation is extended to the following personnel for ideas incorporated into various technical portions of this investigation: Mr. F. Hildebrand, Naval Facilities Engineering Command; Mr. P. Stone and Mr. D. Brunner, Navy Civil Engineering Laboratory; Mr. R. D. Winn and Mr. B. Wasserman, Office of the Chief of Engineers, Department of the Army; and MAJ R. F. Olfenbuttel. Administrative support was provided by Mr. R. G. Donaghy, Chief, CERL-EH.

COL L. J. Circeo is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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PRODUCTION AND USE OF DENSIFIED REFUSE-DERIVED FUEL (DRDF) IN MILITARY CENTRAL HEATING AND POWER PLANTS

1 INTRODUCTION

Background

One objective of the national energy strategy set forth by the President on 29 April 1977 is to reduce dependence on foreign oil and thereby limit vulnerability to supply disruptions.[1] Coupled with this national energy need, the increasing cost, scarcity, and in some places, lack of availability of natural gas has motivated the Department of Defense (DOD)[2] to convert installation heating and power plants to coal as a primary fuel.[3] To meet the challenging goals of the national energy strategy, which call for vast near-term reductions in the use of oil and natural gas as primary fuels, it is probable that the military coal conversion effort will emphasize conventional coal combustion technologies such as spreader-stoker firing, overfeed traveling chain-grate firing, and underfeed retort-stoker firing.[4] However, conversion to coal will be expensive. For example, in addition to the cost of equipment modifications necessary to burn coal at central heating and power plants, there are the added costs and risks involved with removing sulfur dioxide pollutants from flue gases. For a central power plant rated at 100 MBtu per hour, the capital cost of flue gas desulfurization may be as high as $15 million and annual operation and maintenance (O & M) costs can be as high as $5 million.[5] A comprehensive review of the efficiency and reliability of sulfur dioxide scrubbers conducted in FY78 indicated the high risk of implementing such systems as coal-fired boilers.[6]

Using renewable alternative fuels as primary fuels in its heating and power plants is one way the military can help achieve the goals of the national energy strategy. Densified refuse-derived fuel (DRDF) is a renewable alternative fuel which has high potential in military heating and power plants as a substitute for or supplement to coal.[7] DRDF has two major advantages: (1) immediate and sustained availability (it is produced from mixed solid waste and is therefore renewable), and (2) negligible sulfur content, which avoids the costs of flue gas desulfurization from central heating and power plants. Accordingly, industry and the military have conducted several short-term tests on the use of DRDF in central heating and power plants. These tests have indicated that DRDF may show promise for long-term continuous use in such systems.

Because of DRDF's potential as a renewable and environmentally compatible substitute for coal, the Air Force initiated a two-phase study on using the fuel in military heating and power plants. The first phase of the study, documented in this report, was a comprehensive review of literature and facilities to evaluate the state of the art for using DRDF in military-scale systems. The second phase of the investigation will cover laboratory analyses and field investigations to supplement data derived in the first phase and to determine a cost estimate of, and a monitoring protocol for, a long-term military demonstration of DRDF and coal at a central heating and power plant.

The scale and mission of heating and power plants considered in the investigation (those ranging between 25 and 200 MBtu per hour) usually tend to be unique to the military. Often, these plants have special requirements for response to load changes, turndown capability, and vulnerability. This interest in vulnerability focuses on the long-term effects of using a coal substitute in a boiler which, in the case of mobilization, may be required to perform responsively at 100 percent or more of its maximum continuous rating (MCR).

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[1] *Army Energy Plan* (Headquarters, Department of the Army, 1978).

[2] S. A. Hathaway, M. Tseng, and J. S. Lin, *Project Development Guidelines for Converting Army Installations to Coal Use*, Interim Report E-148/ADA068025 (U.S. Army Construction Engineering Research Laboratory [CERL], March 1979).

[3] E. Honig and S. Hathaway, *Application of Modern Coal Technologies to Military Facilities*, Interim Report E-130/ADA055560 (CERL, May 1978).

[4] *Stokers for Industrial Boilers: Assessment of Technical, Economic, and Environmental Factors* (Battelle Columbus Laboratories, 1975).

[5] B. Donahue, S. Hathaway, G. Schanche, and S. Struss, *Evaluation of Alternatives for Restoring the South Boiler House at Joliet AAP to High Sulfur Coal Burning Capability*, Technical Report N-66/ADA069374 (CERL, May 1979).

[6] W. H. Megonnel, "Efficiency and Reliability of Sulfur Dioxide Scrubbers," *Journal of the Air Pollution Control Association* (July 1978).

[7] S. A. Hathaway and R. Dealy, *Technology Evaluation of Army-Scale Waste-to-Energy Systems*, Technical Report E-110/ADA042578 (CERL, July 1977).

Objective

The objectives of this investigation were (1) to determine and evaluate the state of the art in the production and use of DRDF in military-scale central heating and power plants, and (2) to recommend related laboratory analyses and demonstrations for future work.

Approach

1. A comprehensive search and review of literature pertaining to the military-scale production and use of DRDF was conducted. The literature was evaluated with respect to its provision of scientific and engineering data which would be helpful in formulating subsequent research and demonstration goals. The literature consisted of technical reports, technical articles, papers in journals, and unpublished internal reports from companies sponsoring refuse-derived fuel facilities.

2. A comprehensive review of operating technology-based resource-recovery facilities in the United States was conducted. The facilities analysis involved person-to-person contact between research personnel and facility managers and operators. The analysis emphasized facilities which produced a refuse-derived fuel product whose potential production and use by the military might be feasible.

3. Information regarding cost and performance of resource recovery technologies was derived from vendors and manufacturers.

4. Several small support studies pertaining to the overall work of the phase one and two investigations were contracted. These studies involved the disposition of byproducts from DRDF production and use, a facilities analysis, the design of storage and handling facilities, and a protocol for monitoring a demonstration of coal and DRDF at a military central heating and power plant.

5. Based on the evaluation of information obtained in steps 1 through 4, conclusions and recommendations for further research efforts and demonstrations were derived.

2 NATURE AND USE OF DRDF AS A FUEL

Definition

This investigation revealed the existence of numerous, sometimes conflicting, definitions of refuse-derived fuel. The National Center for Resource Recovery defines refuse-derived fuel as the combustible or organic fraction of municipal solid waste which has been prepared for use as a fuel by any of several mechanical processing methods such as shredding and air classification.[8] It is assumed that this definition refers to refuse-derived fuel as a solid-phase fuel. This definition considers municipal solid waste to be the combined residential and commercial waste materials generated in a given municipal area, and, obviously, excludes wastes derived from military installations. On the other hand, the Bio-Energy Council includes refuse-derived fuel as part of a larger system of renewable fuels defined as biomass.[9] According to this source, all biomass-related fuels are cellular in nature and are derived by photosynthetic processes. Hence, biomass can refer to corn, algae, paper, and other refuse components. A biomass fuel may be solid, liquid, or gas. Other sources define refuse-derived fuel as refuse which has been converted into a form usable as a supplementary solid fuel with conventional fossil fuels in an existing or newly designed combustion unit.[10] However, other investigators indicate that refuse-derived fuel can be solid, liquid, or gaseous, depending on the processing to which it is subjected.[11] In contrast, the American Society for Testing and Materials defines refuse-derived fuel as a lightweight shredded material which has been sized to pass through a 1-in. screen, has been density-classified, and has had any ferrous metals removed magnetically.[12] Although this is the accepted definition of refuse-derived fuel (or of a particular type of refuse-derived fuel called RDF-3), it is limiting in that it specifies the technological processing to which mixed solid waste must be subjected in order to derive the defined fuel. Furthermore, this definition limits refuse-derived fuel to a solid. Therefore, densified refuse-derived fuel can be defined better as a refuse-derived fuel processed in a pelletizer, a briquetter, or any similar equipment which increases

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[8] *Glossary of Solid Waste Management and Resource Recovery* (National Center for Resource Recovery, 1977).

[9] *Bio-Energy Directory* (Bio-Energy Council, May 1979).

[10] J. Payne, "Energy Recovery From Refuse: State-of-the-Art," *Journal of the Environmental Engineering Division* (American Society of Civil Engineers, April 1976).

[11] Personal communication between Mr. S. Hathaway (CERL), and Mr. J. Jones (SRI International, Menlo Park, CA) (November 1977).

[12] H. Hollander and J. Kieffer, *Developing Analytical Procedures for Reproducible Determinations of Thermal Chemical Characteristics of RDF* (Gilbert/Commonwealth Company, Reading, PA, December 1978).

the fuel's unit density. Most DRDF tests have used DRDF pelletized in a mechanical extrusion mill. A typical DRDF pellet is 1/8 in. in diameter by approximately 3/8 in. in length. Pellet size is not fixed, but rather is determined by how it will be used.

For this investigation, DRDF was defined as a solid, compacted, combustible fuel derived by mechanically processing and densifying mixed trash and refuse, excluding sludge. This definition was used because it provided the flexibility required to analyze and evaluate facilities which did not produce refuse-derived fuel conforming to the previous definitions. As indicated later, there is no single, established process for producing DRDF. Therefore, it is extremely difficult to consistently define the thermochemical properties of DRDF as it is currently produced. The wide variation in DRDF fuel properties data may be seen as a result of the diversity of production processes, a problem which stems partly from the lack of a definition of DRDF and refuse-derived fuel.

Generic DRDF Production Process

Figure 1 illustrates a generic DRDF production process derived from the analysis of various production theories and facilities. This process includes unit operations presumed by field experience to produce a DRDF that meets the definition used in this study. Presentation of a generic DRDF production process is controversial because there are many different processes. In fact, the number of different processes is equivalent to the number of individuals interested in producing DRDF.[13]

In the generic DRDF production process, delivered solid waste first passes through a primary shredder for initial size reduction and ballistic removal of heavy noncombustibles such as heavy pieces of metal. The shredded product then passes through a magnetic separator for the removal of ferrous materials. Next, the refuse-derived fuel feedstock passes through an air classifier for the removal of heavy materials. The light feedstock passing through the air classifier then passes to a secondary shredder for additional size reduction. The product from the secondary shredder is customarily called fluff RDF. The fluff RDF from the secondary shredder may or may not enter a surge bin for temporary storage. The DRDF is manufactured by pelletizing

[13] S. A. Hathaway, *Recovery of Energy From Solid Waste at Army Installations*, Technical Manuscript E-118/ADA044814 (CERL, August 1977).

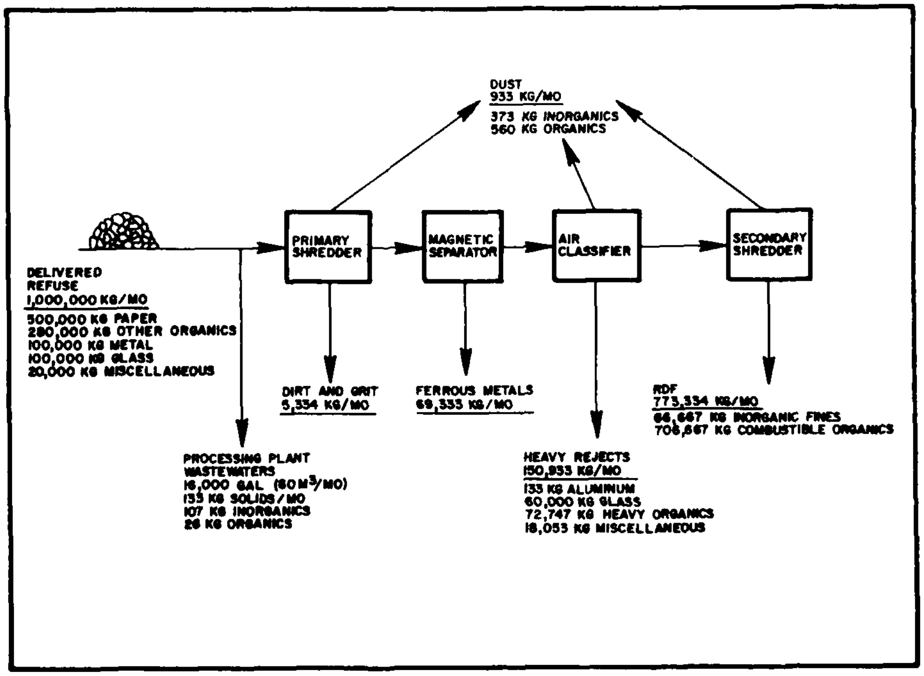

Figure 1. Generic refuse-derived fuel process flow and mass balance. (From *Control and Disposal of By-Products of Refuse-Derived Fuel Production and Use* [SCS Engineers, February 1979]. Reprinted with permission.)

or briquetting fluff RDF. The type of pelletizer commonly used in the DRDF industry is the California Pellet Mill, which works on the principle of mechanical extrusion.

Figure 1 shows the general mass balance of the generic DRDF production process, along with the process itself. The mass balance indicates that approximately 77 percent of the input mass to a generic DRDF production process becomes product DRDF. This product DRDF contains approximately 8.6 percent inorganic fines and 9.4 percent combustible organic material. The mass balance indicates a total loss of organic materials of approximately 1.5 percent of the input.[14] This very small loss of the input organic material is indicative of the ideal DRDF production process; however, actual operating experience indicates that organic losses may be substantially higher.

Figure 1 shows that using mixed solid waste to produce refuse-derived fuel does not result in closedown of solid waste disposal facilities, contrary to many claims made in the refuse-derived fuel industry. As indicated above, no more than 77 percent of the input mass becomes refuse-derived fuel. The remaining 23 percent of the input mass consists of dirt, grit, and other process rejects which will require ultimate disposal, ferrous metals which may be recycled, and other potentially recyclable materials such as aluminum and glass. Hence, for the average military installation, which in peacetime generates approximately 35 tons per day of solid waste, 27 tons of generic refuse-derived fuel will be produced, and 8 tons of rejects and potentially recyclable materials must be disposed of or used.

Justification for DRDF Production and Use

Whether occurring in the civilian sector or on a military installation, the production and use of DRDF is part of the larger overall category of resource recovery. The Mitre Corporation has identified the central considerations associated with resource recovery planning and procurement. These issues pertain to the production and use of DRDF, both in the civilian and military sectors. According to Mitre,

> It is quite clear that resource recovery systems have a number of characteristics which make their planning and procurement much more complex than that of such traditional public works projects as waste treatment plants and wastewater facilities. Perhaps the most important characteristic is that a resource recovery facility is, in reality, a business venture with the accompanying business risks and financial requirements that are an integral part of any business enterprise. Planning for resource recovery requires consideration of solid waste input (the raw material) and conversion of this input into materials and/or energy products. Involved parties must agree to long-term contracts for both waste input and purchase of energy products as security for project financing. Because of the nature of such contracts, each party must accept certain risks associated with the project.[15]

Among the issues which must be addressed in implementing any resource recovery system, including the production and use of DRDF, are the nature and severity of solid waste dispoal problems, the technical and economic feasibility of resource recovery as a disposal option, the technical and economic feasibility of resource recovery as an energy-saving option, planning for system implementation, and executing a system procurement.

Within both the Department of Defense and the civilian sector, the motivation for producing and/or using DRDF is economic. In the planning stages for a DRDF project, a cost/benefit life-cycle analysis is normally conducted to determine whether the proposed project will have a desirable economic payoff. When energy-conservative construction is considered within the military, a desirable payoff is a period of time usually equal to or less than 10 years after project startup. Similarly, the implementation of a DRDF system is viewed as a business venture which will reduce costs; thus, a comparative cost analysis must be conducted between the present system and the DRDF system. Within the military, a present or baseline system is usually the disposal of solid waste, most often by landfill. The capital and recurring costs of producing and/or using DRDF must be compared with this baseline system. To determine these costs, it is vital to obtain accurate information about the capital expenditure and other first costs—e.g., for startup and field alignment. In addition, recurring costs must be included in a life-cycle analysis. It is important, therefore, to have actual field information regarding (1) the quantity of manpower which must operate the system, (2) the amount of water, auxiliary fuel, and electrical power required to operate the system, and (3) the levels of routine maintenance and repair required to keep the

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[14] *Control and Disposal of By-Products of Refuse-Derived Fuel Production and Use* (SCS Engineers, Long Beach, CA, February 1979).

[15] *Resource Recovery Implementation: An Overview of Issues* (Mitre Corporation, October 1978).

system operating throughout its economic life. In addition to the costs of operating and maintaining the production and/or use facility, information pertaining to the future avoided costs must also be accounted. When DRDF replaces coal as a primary fuel or is added as a supplement to coal, the future avoided costs are the costs of the conventional fuel (coal) and other avoided costs, such as that of desulfurizing flue gas. As indicated previously, the capital cost of flue gas desulfurization systems alone may be as much as $15 million per military central heating or power plant. Future avoided costs of conventional fuel, including coal, may ultimately be very substantial because of the current nationwide fuel supply problems. The manner in which comparative life-cycle costs are determined and evaluated is well documented within the services.[16]

Whether a military installation can consider itself candidate for producing and/or using DRDF largely depends on the outcome of the comparative life-cycle analysis of all the options open to it. In evaluating these options, it is imperative that the military planner have at his/her disposal accurate and precise information about the production and use of DRDF.

It is important to understand the concepts of accuracy and precision insofar as resource recovery systems and life-cycle economic analyses are considered. Woodyard provides an excellent review of the two terms as they pertain to solid waste characterization for resource recovery.[17] He points out that although the two terms are often used synonymously, their technical meanings are substantially different. Accuracy refers to the closeness with which an estimate approximates the true value of the parameter being measured. Precision refers to the repeatability of the measurements used to produce the estimate. Data can be precise but inaccurate, or accurate but imprecise. Because of both the manner in which military present-value, life-cycle analyses are conducted and the high sensitivities of such analyses to high-escalation items such as fuel savings, small deviations in either accuracy or precision of estimates will result in bottom-line distortion of the costs and benefits of the facility as it will actually operate.

Prior to the economic analysis, the military planner must have accurate and precise information regarding the technology involved to produce and/or use DRDF in an installation central heating or power plant. Accurate and precise understanding of the technology is central to the planning, programming, and implementation of the facility. When the military installation is considered a candidate for producing DRDF, the planner must be aware of the entire set of boundary conditions pertaining to the production process. When the installation is a candidate for using DRDF either as a supplementary fuel or as a substitute fuel for coal in a central heating or power plant, the planner must understand the equipment modifications that may be required for reliable long-term use of this fuel. Only then can accurate and precise economic analyses be conducted and a reliable determination made of whether the system under consideration will have a reasonable payoff.

The average military installation generates approximately 35 tons per day of solid waste in peacetime. The largest military installation may generate as much as 120 tons per day of solid waste. In peacetime, few military installations generate solid waste in quantities comparable to the magnitude generated in large municipalities such as Chicago[18] where far more than 1000 tons per day of solid waste are generated.[19] The refuse-derived fuel production facility in Ames, IA, which is considered small by industry standards, generates far more solid waste than a typical military installation in peacetime. At Ames, approximately 150 tons per day of solid waste are processed into a refuse-derived fuel for use in a nearby heating and power plant.[20] It has been pointed out that the solid waste generation of a typical peacetime military installation resembles that of a small community.[21] Accordingly, it can be deduced that a military installation lacks the economy of scale required to implement a DRDF production facility.

It is highly probable that the role of military installations with respect to DRDF will be as a user rather

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[16] *Economic Analysis Handbook*, Naval Facilities Engineering Command Document P-442 (Naval Facilities Engineering Command, June 1975).

[17] J. Woodyard, *Municipal Solid Waste Survey Protocol* (SCS Engineers, Long Beach, CA, April 1978).

[18] *The Chicago Northwest Incinerator* (City of Chicago, 1977).

[19] C. St. Clare, "Resource Recovery Update," *Pollution Engineering* (September 1978).

[20] R. Holloway, "Comparing the Ames and St. Louis Resource Recovery Projects," *Waste Age* Vol 9, No. 2 (February 1978).

[21] A. Helmstetter, "Resource Recovery for the Small Community: What Are the Options?", *Solid Waste Management* (November 1978).

than as a producer. In this role, the military installation will probably interact with a civilian solid waste resource recovery facility, perhaps even hauling its own solid waste to that facility and contributing a portion of the capital cost. In return, the military installation will receive a specified DRDF product for use in its central heating or power plant. To determine whether such a strategy is economically beneficial to DOD, the military planner must have a technical understanding of the potentials and the drawbacks of using DRDF either as a substitute fuel or as a supplementary fuel in an existing heating or power plant. In addition, he/she must be able to specify the product DRDF to be received from the civilian sector processing plant. When the installation itself may produce DRDF, he/she must be aware of the product's fuel properties. Knowing the fuel properties, the planner and enlisted experts can determine how the fuel will perform in a system designed for coal and then deduce whether the use of DRDF would be beneficial.

Fuel Properties of DRDF

In any fuel substitution problem, it is vital to know certain properties of the fuel which will be substituted (Table 1). These properties have been well documented elsewhere and need not be detailed here.[22] Of primary interest are the proximate analysis, the ultimate analysis, and the calorific value of the fuel. Of additional interest are the fuel's ash properties and other physical/chemical properties as they pertain to the specific firing equipment being considered to fire DRDF.

Table 1 summarizes data on the proximate analysis, ultimate analysis, and calorific values of DRDF. These data were collected during the literature review portions of the investigation, as indicated by the references in Table 1. In Table 1, the production processes leading to the various types of DRDF for which the analyses are given differ widely. Accordingly, one would expect a wide variation in the analyses of the fuel, which is also shown in the table. Moisture contents as low as 10 percent and as high as 26.2 percent are evident. Volatile matter can range between 40 and 63 percent, while ash content can range between 9 and approximately 25 percent. The calorific value of the DRDF for which data are available ranged between 3757 Btu/lb to more than 6600 Btu/lb.

[22] *Steam* (Babcock and Wilcox Company, 1978); *Combustion Engineering* (Combustion Engineering Company, 1969).

Table 1
Fuel Properties of DRDF

Proximate Analysis (wt %)				Ultimate Analysis (wt %)						Btu/lb	Reference
H_2O	Volatiles	Fixed Carbon	Ash	C	H	O_2	N	S	Ash	(Dry Basis)	
13.6	47.0	43.0	10.3	66.0	NA	NA	NA	0.49	10.3	11,040*	+
16.5	63.7	10.38	9.02	NA	NA	NA	NA	0.22	9.02	6,382	†
26.0	46.0	4.0	25.0	NA	NA	NA	NA	–	25.0	3,757	**
26.2	NA	NA	14.8	42.4	6.0	33.5	3.3	–	14.8	NA	++
NA	NA	8.027	24.95	41.2	4.5	28.7	0.6	0.1	24.95	NA	††
10.3	51.8	16.9	20.6	34.92	5.16	31.18	0.74	0.5	23.00	6,680	***
10.0	40.5	38.0	11.5	39.6	5.3	32.3	0.9	0.1	11.5	6,000	+++

*Mixed 2:1 by volume with bituminous coal.

+J. W. Jackson, *A Bioenvironmental Study of Emissions from Refuse-Derived Fuel*, Report No. 76 M-2/ADA024661 (USAF Environmental Health Laboratory, McClellan AFB, CA, January 1976).

†*Preliminary Test Report on Handling and Combustion Characteristics of Franklin Pelletized Fuel and Coal Mixes* (Black-Clawson Co. Fiber Claim, June 1975).

***Solid Waste Fuel Modifications Second Series Burn Tests, Final Report* (Eugene Water and Electric Board, Eugene, OR, December 1974).

++*Conversion of Central Heating Plant Boiler to RDF Firing at Ft. Monmouth, NJ* (W. F. Cosulich Associates, 1975).

††*Solid Waste Management Technology Assessment* (General Electric Company, 1975).

****A Field Test Using Coal: DRDF Blends in Spreader Stoker Fired Boiler* (Systems Technology Corporation, 1978).

+++S. A. Hathaway and R. Dealy, *Technology Evaluation of Army-Scale Waste-to-Energy Systems*, Technical Report E-110/ADA042578 (CERL, July 1977).

It is important to note that analytical methods for determining the proximate analysis, ultimate analysis, and calorific value of DRDF are currently being reviewed by the American Society for Testing and Materials. The Society undertook this investigation when it became apparent that the analytical procedures for determining the fuel properties of coal did not necessarily apply to determining the fuel properties of DRDF or any other type of refuse-derived fuel. The data on fuel properties of DRDF shown in Table 1 presumably were derived by applying standard procedures for the analysis of coal to the analysis of the DRDF. It can only be speculated if and how these data will change when more refined procedures are developed and applied to DRDF analysis. Despite the fact that the data show wide variation, it is customary in conventional combustion calculations to assume that the refuse-derived fuel is entirely cellulosic in nature. Cellulose has a chemical composition of $C_6H_{10}O_5$. Again, it can only be speculated whether the theoretical combustion calculations which assume that DRDF is cellulosic compare to any field experience with DRDF. More than 20 DRDF tests have been conducted, and to date, there are few data to confirm or reject the hypothesis that the material is entirely or nearly entirely cellulosic, or whether the assumption that the material is cellulosic in nature is sufficient for the conduct of combustion equations.

Contrary to the situation regarding proximate analysis, ultimate analysis, and calorific value, there are some rather reliable data on the fusion temperatures of residue constituents and the melting points of pure metals typically found in DRDF (see Table 2).[23] The data shown in Table 2 were derived from laboratory analyses using standard methods for analyzing coal ash. This research did not reveal any actual field investigation of the properties of ash derived from burning DRDF. However, there is general agreement among resource recovery researchers and engineers that the ash properties of DRDF and other types of refuse-derived fuel will limit allowable furnace temperatures. At temperatures above approximately 1900°F, the

[23] S. A. Hathaway and R. Dealy, *Technology Evaluation of Army-Scale Waste-to-Energy Systems*, Technical Report E-110/ADA042578 (CERL, July 1977).

Table 2
Fusion Temperatures of Residue Constituents and Melting Points of Pure Metals

(From S. A. Hathaway and R. Dealy, *Technology Evaluation of Army-Scale Waste-to-Energy Systems*, Technical Report E-110/ADA042578 [CERL, July 1977].)

	Initial Deformation	Softening (Oxidizing Atmosphere)	Fluid
Clear Glass	1480 (804)	1680 (916)	1840 (1004)
Brown Glass	1620 (882)	1740 (949)	2080 (1138)
Green Glass	1640 (893)	1800 (982)	2080 (1138)
Ash from:			
Garbage	2020 (1104)	2140 (1171)	2200 (1204)
Cardboard, corrugated	2060 (1126)	2160 (1182)	2240 (1227)
Misc. paper	2160 (1182)	2300 (1260)	2480 (1360)
Grass and dirt	2080 (1138)	2240 (1227)	2320 (1271)
Textiles	2040 (1116)	2180 (1193)	2240 (1227)
Heavy plastics, leather, rubber	2100 (1149)	2220 (1216)	2300 (1260)
Bones and shells	2800 (1538)	2800 (1538)	2800 (1538)
			Melting Points, °F (°C)
Iron			2795 (1535)
Iron oxide (Fe_2O_3)			2849 (1565)
Aluminum			1200 (649)
Aluminum oxide (Al_2O_3)			3713 (2045)
Lead			622 (328)
Tin			449 (232)
Zinc			769 (409)
Lime (CaO)			4676 (2580)
Silicon oxide (SiO_2)			2930 (1610)

temperature-viscosity relationship of refuse ash and ash from refuse-derived fuels of different types is such that the ash becomes sticky and adheres to relatively cold surfaces such as heat transfer tubes. Therefore, most experimentation with DRDF and other types of refuse-derived fuels has aimed at keeping furnace temperatures below this point.

Early attempts to apply standard coal methods to determine the volatility of refuse-derived fuel indicated that these methods do not apply to the analysis of DRDF.[24] During these analyses, it was suggested that refuse-derived fuel was more volatile than coal. This was first noted by Hollander, who wrote that the time required for volatilization of any fuel can indicate the potential rate of reaction or heat release.[25] Accordingly, the U.S. Army Construction Engineering Research Laboratory (CERL) conducted investigations to determine the time-related profiles of volatilizing refuse-derived fuel and coal. Preliminary investigations on burning RDF and coal in a muffle furnace were published in 1977.[26] Broadened follow-on investigations were later conducted by the Army.[27] In these investigations, the ignition and combustion rates of three types of DRDF and low-volatile Illinois bituminous coal were investigated at temperatures ranging from 600°C to 1000°C and residence times ranging up to 120 seconds. DRDF ignition time was found to be 12 times less than that of coal, and the temperature required for coal ignition at a given residence time was greater than that needed for DRDF ignition; in addition, the DRDF-to-coal time to ignition ratio was found to be expressible as a linear function of furnace temperature. These experiments also indicated that DRDF produced from mixed municipal residential solid waste has a slower combustion rate than that produced from homogenous heavy paper stock and that the combustion rates of all types of DRDF were significantly greater than that of the coal tested. The findings from these investigations compared very well with the Pittsburgh Energy Research Center's findings on the reactivity and gasification characteristics of low-ranking coals and potentially reducing waste materials.[28] Moreover, the findings from both of these investigations compared well to findings from a 1971 MIT study.[29] For the MIT study, a versatile batch-type incinerator was designed and built to determine the effect of operational variables on the ignition and burning rates of DRDF placed in a fuel bed under conditions similar to those of a municipal incinerator. In this study, a simulated refuse consisting mostly of wood blocks was used. The rates of combustion and propagation of ignition discovered in this experiment compared well with the findings of both the Pittsburgh Energy Research Center and the Army.

The present investigation did not uncover any field data from DRDF tests which pertained to the actual combustion rate of the material. However, in the short-term DRDF tests evaluated, it has been common experience that the feed rate of DRDF must be increased well beyond the limits normally set for coal to maintain furnace heat. This is probably because the DRDF has a lower ignition temperature and a higher rate of volatilization, and therefore, combusts essentially completely more rapidly than coal. Accordingly, the achievable turn-up feed rate of a boiler is limiting when considering the use of DRDF as either a supplement to or substitute for coal.

Table 3 lists other fuel properties that are of interest when considering the use of DRDF in an existing heating or power plant.[30] These properties are listed in Table 3, along with the most probable type of firing method to be used within DOD. The properties are as-fired size consist, moisture, caking index, ash fusibility, grindability, friability, volatile matter, fixed carbon, ash content, heating value, ash viscosity, ash composition, sulfur content, chloride content. The types of firing methods to be considered are underfeed retort firing (both single and multiple retort), traveling-

[24] S. A. Hathaway, "Potential Systems for Energy Recovery From Solid Waste at Military Installations," *Proceedings of the Second Energy/Environment Conference* (American Defense Preparedness Association, Kansas City, MO, March 1977).

[25] H. Hollander, *Processed Refuse A Salvage Fuel for Existing Boilers* (Gilbert/Commonwealth, Reading, PA, June 1977).

[26] S. A. Hathaway and J. S. Lin, "Combustion Rates of RDF," *Proceedings of the Third International Conference on Environmental Problems of the Extractive Industries* (November 1977).

[27] S. A. Hathaway and J. S. Lin, *Thermogravimetric Analysis of Solid Refuse-Derived Fuels and Coal*, Technical Report E-149/ADA067829 (CERL, March 1979).

[28] *Reactivity and Gasification Characteristics of Low-Ranking Coals and Potentially Reducing Waste Materials* (Pittsburgh Energy Research Center, March 1976).

[29] G. Williams, A. Sarofim, J. Howard, and J. Rogers, *Design and Control of Incinerators* (Chemical Engineering Department, Massachusetts Institute of Technology, 1970).

[30] S. A. Hathaway and R. Dealy, *Technology Evaluation of Army-Scale Waste-to-Energy Systems*, Technical Report E-110/ADA042578 (CERL, July 1977).

Table 3
Combustion Performance Vs. Solid Fuel Properties

(From S. A. Hathaway and R. Dealy, *Technology Evaluation of Army-Scale Waste-to-Energy Systems,* Technical Report E-110/ADA042578 [CERL, July 1977].)

Very Important 1
Important 2
Minor Importance 3
Little Importance 4

Solid Fuel Property	Solid Fuel Firing Method: Underfeed Single Retort	Underfeed Multiple Retort	Traveling Grate	Spreader Stoker
As-Fired Size Consist	1	2	2	1
Moisture	3	3	4	3
Caking Index	2	2	1	3
Ash Fusibility	2	2	3	3
Grindability	4	4	4	4
Friability	3	3	3	3
Volatile Matter	3	3	3	3
Fixed Carbon	4	4	4	4
Ash Content	3	3	2	3
Heating Value	4	4	4	4
Ash Viscosity	3	3	3	3
Ash Composition	*			
Sulfur	**			
Chlorides	**			

*Affects fireside fouling; not important to combustion.

**Important from corrosion standpoint, not vital to combustion.

grate firing, and spreader-stoker firing. Table 3 lists the relative importance of each fuel type with respect to the firing method. The most important fuel properties appear to be as-fired size consist, caking index, ash fusibility, and ash content of the fuel. Ash viscosity, friability, and volatile matter are all of secondary importance, but still must be considered in the conversion.

The as-fired consist of the fuel and the caking index were investigated in this study, and it appears that there are virtually no DRDF-related data pertaining to these variables. Very few data have been reported for ash content and ash composition. As shown in Table 1, the ash content can vary between 9 and approximately 25 percent by weight in the fuel. No conclusive analyses pertaining to the composition of refuse ash have been conducted.

Because it is probable that the military will not produce DRDF, but rather will use civilian-produced material, the military planner must write specifications for procuring the fuel.

The military fuel procurement process usually operates on an annual basis. Only rarely and in outlying areas such as Alaska do fuel procurement agreements exist beyond 1 year. However, the same supplier may provide fuel to an installation every year; such an agreement usually requires renegotiation. In the FY78 Military Construction Authorization Bill, the Senate Armed Services Subcommittee considered the possibility of a long-term (10-year) contract between military installations and civilian authorities in which the military would purchase refuse-derived fuel and perhaps pay a share of the capital cost of the civilian-located facility.[31] Such an arrangement would not be unprecedented, since many DOD installations now pay some of the costs of regional water or sewer systems. This Senate endorsement enables an installation to draw up a long-term contract for purchasing DRDF as an alternate fuel. Such an endorsement makes a business venture by civilian resource recovery authorities less of a risk than a 1-year agreement when an installation is foreseen as a DRDF purchaser.

[31] *Military Construction Authorization,* Fiscal Year 1978, Report #95-125, Senate Armed Services Committee (1978).

To capitalize on the opportunity to enter into long-term DRDF purchase agreements, the military must be able to effectively specify the product it will purchase by defining the DRDF to be purchased and its essential fuel properties and/or performance. Consideration of the furnace and boiler system design parameters must be made. This is the traditional long-established approach to the fuel substitution problem.

Despite the fact that long-term DRDF procurement agreements are now possible, there is still no industry-wide resolution for defining DRDF. Moreover, the essential fuel properties of DRDF have not yet been determined adequately. In fact, an American Society for Testing and Materials subcommittee has the specific task of developing analytical methods which can be applied accurately and precisely to reveal DRDF fuel properties. Hence, any long-term agreement to purchase DRDF would not entail some risk to a military installation. A major risk is that a DRDF facility operation will not run smoothly during its first few years. Accordingly, a military installation should not expect products of constant quality to be delivered during that time. A second risk is that DRDF fuel properties may be unknown or not determinable. Hence, using DRDF may render deleterious long-term effects to a heating or power plant system. During mobilization, when the heating or power plant may be required to operate at more than 100 percent of MCR for up to 4 or 5 hours per day, such unforeseen long-term deleterious effects may cause plant outage, which will adversely affect the installation mission.

This investigation found that when DRDF is being considered for use in an existing heating or power plant, specifications for its purchase are more likely to pertain to what is marketed and available rather than to what is needed. This approach is possibly the result of the many DRDF tests conducted during the past 5 years in which an available or marketed product, DRDF, was purchased in some minor quantity and fed into an existing heating or power plant. The effects of using DRDF both as a supplement with and as a substitute for coal then have been recorded by researchers and engineers at the site. Following these short-term tests, some deduction was made concerning the efficacy of using DRDF over the long term as a coal substitute or supplement. Unfortunately, it is possible that the inertia of this approach which began on the testing level will carry over into the specification, procurement, and implementation levels with possible long-term deleterious effects on installation energy production capabilities.

The most notable specification for procuring DRDF has been issued by Wright-Patterson Air Force Base in Ohio.[32] This specification calls for a delivered RDF pellet that is 1/2 in. in diameter and optimally 1/4 in. in length, having a dry basis heating value of at least 7000 Btu per pound, a maximum ash content of 15 percent, a maximum moisture content of 20 percent, a bulk density of 35 lb per cubic foot, and a maximum fines content of 5 percent. Up to 4000 tons per month will be delivered between 1 March 1981 and 30 September 1988. This specification may be a model for DOD-wide DRDF procurement. However, it remains to be seen whether the supplied DRDF (at least for the first few years of this supply period) will meet the specifications.

The fact that there is neither a definition of DRDF nor a definitive way of determining its properties severely affects the feasibility of using DRDF in military heating or power plants. As noted above, it could result in the tendency to specify and procure what is available and marketed rather than following traditional fuel substitution approaches by examining the design parameters of the combuster to determine the quality of product which will be supplied. The traditional approach toward fuel substitution in heating and power plants has a long history of success.[33] Following this traditional approach, which will result in a reliable operating system, requires thorough cognizance of the

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[32] *Specifications for Purchase of Refuse-Derived Fuel for Coal-Fired Heating Plants* (Wright-Patterson Air Force Base, OH, Engineering and Construction Branch, Civil Engineering Squadron, September 1977).

[33] W. F. Coles and J. T. Stewart, *Considerations When Converting Industrial Plants to Coal Firing*, Paper 77-IPC-Fu-1 for meeting 24-26 October 1977 (American Society of Mechanical Engineers; O. DeLorenzi, "Influence of Low-Quality Coal on Pulverized Fuel-Fired Units," *Combustion* (November 1952); J. D. Blue, J. L. Clemant, and V. L. Smith, *Effect of Coal and Multi-Fuel Firing on Industrial Boiler Design*, TAPPI Eng. Conf. Paper, October 1974, Paper 12-3, pp 211-230; S. Suda, "Fuels and Their Effects on Power Design for the Pulp and Paper Industry," *American Paper Industry*, Vol 56, No. 1 (1974), pp 19-23; L. Fischer, "Converting a Steam Boiler Plant to Oil Firing," *Heating and Ventilation* (April 1963); J. Meyler and J. Lang, "Operating Experience on Boilers Designed for Firing Coal or Oil," *Journal of the Institute of Fuel* (September 1963); D. Gunn, "The Effect of Coal Characteristics on Boiler Performance," *Journal of the Institute of Fuel* (July 1952); "Conversion of Two Oil-Fired Water Tube Boilers to Natural Gas," *Steam and Heating Engineer* (February 1972); D. Hubert, "Integrating Coal Properties With Boiler Design," *Combustion* (April 1959); A. Bogot, "Operation and Maintenance of Steam-Generating Equipment as Affected by Properties of Fuels," *Combustion* (October 1949).

fuel being considered; such knowledge has been found to be spotty, superficial, and generally lacking in the resource-recovery industry.

Summary of Nature and Use of DRDF as a Fuel

This investigation found general disagreement on the definitions of DRDF and refuse-derived fuel. However, there is intuitive knowledge within the resource-recovery industry that DRDF is a compacted solid fuel produced by mechanically processing mixed trash and refuse. This is the working definition under which this investigation is being conducted.

The investigation revealed only scattered data on the essential fuel properties of DRDF. Such data are required when following the traditional approach toward fuel substitution, which is analyzing the essential design parameters of the combuster candidate for firing a substitute or supplementary fuel, and then specifying the fuel product to be used in that combuster. In the case of DRDF, there are few data pertaining to the essential fuel properties which must be known before an assessment can be made. Therefore, there is an implicit general tendency to accept the DRDF that is marketed and to attempt to use that as a substitute or a supplement fuel in a combuster.

Currently, there appears to be no alternative to this approach. The American Society for Testing and Materials is now developing analytical procedures for determining the essential fuel properties of DRDF. Because of lack of analytical procedures, there is uncertainty regarding exactly what the fuel properties of DRDF are.

Although DRDF, principally because of its negligible sulfur content, appears to be a promising potential fuel for use in military heating and power plants, its implementation is slowed because its essential fuel properties cannot be identified. Therefore, there is some danger in using it in military central heating and power plants. There is risk in becoming bound by long-term agreements necessary to stimulate industry to invest in costly resource-recovery plants. One risk to the military is the potential deleterious, long-term effects that the use of this substitute fuel might have on the combuster, and its constant readiness for full-scale operation in case of mobilization. This full-scale operation may use DRDF or the original design fuel, usually coal. Whatever the case, if the fuel properties of the DRDF used in the combuster are unknown, then the deleterious effects over the long term are also largely unknown. Therefore, there is a clear risk to potential mission support under mobilization conditions if DRDF is used at this time.

3 PRODUCTION OF DRDF

Perspective on Waste as Fuel

Burning as a disposal alternative to land burial of solid waste originated many centuries ago. From the earliest civilizations, the burial of wastes has always been comparatively easy in rural areas and was even specified by Moses as a required practice for Israel.[34] Numerous references are made in the historical literature about the great heaps of garbage in open dump areas throughout the development of civilization. Particularly noteworthy was the situation of London. Throughout its growth, the city was littered with vast heaps of discarded trash and garbage. So severe was the health hazard associated with these piles that an authority on the history of technology indicates that the great fire of London in 1666 had a "great purifying effect and for some time caused complaints about refuse in the streets to cease."[35]

The first incinerator (a facility devoted to the burning of refuse) was designed in England in 1874. Shortly thereafter, a refuse destructor and boiler were combined, in which the heat of the boiling water and hot gases was said to prepare the refuse for combustion.[36]

The first application of waste incineration for the direct production of steam appears to have been in Britain around 1878. Even then, energy production was a concern, and heat-recovery incinerators were termed "destructors of that which is evil and offensive and a conserver of that which is beneficial and good."[37] Then, as now, there was widespread argument among members of professional societies concerning the efficiency of using waste as an energy resource. These debates focused on heat-recovery incinerators, and their content often paralleled what currently is being debated among engineers in the United States and Europe.

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[34] D. Wilson, "History of Solid Waste Management," *Handbook of Solid Waste Management* (Van Nostrand Reinhold, 1977).

[35] A. Singer, *A History of Technology*, Vol 4, Oxford, England (1958).

[36] C. Jones, *Refuse Destructors*, London, England (1894).

[37] C. Jones, *Refuse Destructors*, London, England (1894).

In 1893, Tomlinson synopsized the debate as follows:

> The utilization of the waste heat of destructors for the generation of steam is rigidly limited by this consideration, that the efficient performance of its primary function as a destructor shall not be impaired. If the makers of destructors, in trying to fulfill the requirements of maximum steam production, impair the valuable qualities of a destructor – the results of 17 years continuous improvement – it will be bad for them and bad for municipal electric lighting; they will, in all probability, convert an extremely valuable destructor into a combination of an inefficient destructor and a bad boiler. The safe line of progress lies in making the destructor as perfect as possible as a destructor (on the lines of recommendations in the London County Council Report), passing the gases, after they have performed their destructor functions, through a suitable boiler, and taking the result for what is it worth.[38]

There is now similar debate with respect to using DRDF in existing heating and power plants designed for coal. Some argue that using DRDF in existing coal-designed systems will derate the systems by as much as 30 percent below design maximum steam-generating capacity. According to advocates of this strategy, such plants hardly ever, if at all, operate above the point to which they would be derated. This group recommends optimizing the production of DRDF to maximize the reduction in waste disposal requirements. The second group argues that coal-designed heating and power plants should fire a DRDF which will allow them to operate at design maximum steam-generating capacity. This group is more fuel-conscious than the first group and wants to optimize DRDF production so that an optimum product will be available.

Both groups agree on the necessity for using mechanical equipment to process as-discarded solid waste into a burnable fuel. The mechanical processing of solid waste is not new. More than 70 years ago in Britain, household refuse was mechanically processed to remove clinkers and wasted coal which could be recycled as a valuable, usable fuel. A typical solid waste characterization for London at that time was: breeze (cinders and ashes); fine dust; vegetable, animal, and various mineral matters; waste paper; straw and fibrous material; bottles; coal and coke; tins, crockery; bones; broken glass; rags; and iron. Cinders and ashes, which had some heating value when recycled from discarded refuse, averaged approximately 64 percent of the household solid waste stream, while coal and coke averaged approximately 0.84 percent.[39] Once removed from the as-discarded waste, these discarded fuels were then recycled to supply fuel for home heating.

The use of mechanically pelleted waste fuel is not new either. In a pamphlet dated 1603, Sir Hugh Platt referred to the manufacture at that time of a "compressed fuel," but subsequent available records appear to show that briquettes were first manufactured around 1842 in France. This was followed by the first fuel briquetting works in England in 1846. In 1861, fuel briquettes made from brown coal (or lignite) were being made in Germany.[40] In the final report of the British Royal Commission on Coal Supplies in 1905, briquetting is referred to as follows:

> Hitherto this industry has been mainly confined to South Wales where the small coal made in the screening and in the transit of the best steam coal is mixed with 8 percent to 10 percent of pitch and converted into briquettes. Large quantities of similar small coal are exported to the continent for the same purpose.[41]

The briquetting of low-grade and waste fuels flourished in England and in Europe during the early part of the 20th century, and there is evidence that it flourished until World War II.

The best available evidence indicates that the densification of low-grade and waste fuels began in the United States around World War I. A great deal of theoretical work and practical experimentation on fuel briquettes from waste wood and sawdust was conducted at about the time of the Depression.[42] The technology for producing a densified fuel from such a material involved grinding and pelleting. During the 1920s, the Ford Motor Company experimented with the use of pelleted low-grade and waste fuel in some of its coal-fired boilers, but there is little documentation about the success or failure of such experimentation.

The modern origin of DRDF appears to have been in 1972 when beneficiated solid waste cubettes were tested for steam generation in a coal design boiler at

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[38] T. Tomlinson, "The Utilization of Town Refuse for Power Production," *The Electrical Review*, London, England (1893).

[39] C. Jones, *Refuse Destructors*, London, England (1894).

[40] F. Goodrich, *The Utilization of Low-Grade and Waste Fuel*, London, England (1924).

[41] *Final Report of the Royal Commission on Coal Supplies, Part II: General Report*, London, England (1905).

[42] C. Basore, *Fuel Briquettes From Southern Pine Sawdust*, Doctoral Dissertation (Columbia University, 1929).

Fort Wayne, IN.[43] In these experiments, a Fort Wayne corporation, the National Recycling Corporation, collected, received, and processed solid wastes generated in industries and in the municipality. The solid waste processing line included a primary shredder, an air classifier, a magnetic separator, two screening stages, and a cubetter. The cubettes produced were approximately 1 1/2 x 1 1/2 x 2 in. The pellets had a moisture content of 15 percent, a volatile matter content of 65 percent, a fixed carbon content of 14 percent, and an ash content of 6 percent. They contained negligible sulfur and had a heating value of approximately 6800 Btu per pound. A modified John Deere stationary alfalfa cuber was adapted to produce the solid waste cubettes. This equipment had a nominal capacity of approximately 10 tons per hour, depending on the percentage of paper fiber in the material fed to the machine. Preliminary burning trials conducted by Hollander and Cunningham using a 3:1 coal-to-cubette ratio indicated that there were no apparent operating difficulties with the equipment. The tests conducted by Hollander and Cunningham were conducted approximately 11 years after work by Stirrup in burning processed and briquetted refuse at the Zurich City Gas Works in Switzerland. Documentation pertaining to the Swiss tests was not found during this investigation.

Since the tests conducted at Fort Wayne by Hollander and Cunningham, there has been great and widespread interest in the production and use of DRDF as a supplementary or substitute fuel in coal-designed heating and power plants. As indicated later in this report, many similar short-term tests have been conducted with varying degrees of success and failure, particularly in relation to their contribution to the scientific understanding of DRDF production and use.

Review of Current Operations

In its 1978 annual summary report of solid waste processing facilities, the American Iron and Steel Institute lists 266 solid waste processing facilities in the United States which are being planned, built, or operated. Of these, 136 are currently in the planning and study stage, 28 are in design, 8 are in pilot plant operation, 23 are under construction, and 71 are operational.[44] Of the 71 operational facilities, fewer than 12 are oriented toward the production of refuse-derived fuel at a scale that would be beneficial to a military installation. These facilities are in Ames, IA; Baltimore, MD; Bridgeport, CT; Chicago, IL; Brockton, MA; Hempstead, NY; Lane County, OR; Madison, WI; Milwaukee, WI; and Rochester, NY.

Two other facilities have the potential to provide technology transfer to the military departments on solid waste processing and the use of refuse-derived fuel: the National Center for Resource Recovery in Washington, DC, and the Charleston, SC, Solid Waste Reduction Facility. Unfortunately, neither of these facilities has generated very much scientific information about solid waste processing. The National Center for Resource Recovery has a pilot-scale solid waste processing plant designed to produce pellets of refuse-derived fuel. The combustion performance of these pellets has been tested in Hagerstown, MD, and Erie, PA, under EPA contract; however, no definitive reports have yet been published on either the production of the DRDF or on its performance during the tests. The country's oldest solid waste shredding facility is located in Charleston, SC. The plant consists of three parallel operating solid waste shredders to accept solid waste generated within the City of Charleston and surrounding small municipalities. This operation is essentially a size reduction operation known as a shred and spread operation. The shredded solid waste is landfilled adjacent to the solid waste size reduction plant.

Tables 4 and 6-14 are fact sheets on each of the 10 solid waste processing plants listed above, providing the current status of each plant and its capacity, product, process equipment, and economic information. Figures 2 through 10 indicate the flow of the refuse-derived fuel production process for each plant described in Tables 4 and 6-14. Few performance and economic data pertaining to unit operations involved in DRDF production were available from the plants, because such data are not monitored or recorded. Moreover, only in the most unusual case was there a determination of the nature of the solid waste delivered daily to the facility. In addition, data in Tables 4 and 6-14 under the "Products" category are only plant estimates which usually were contrived during the facility's planning stages. The following subsections provide detailed information on the operation of each plant.

Ames, Iowa

This facility (see Table 4 and Figure 2) processes approximately 150 tons of solid waste received daily from the City of Ames and small surrounding com-

[43] H. Hollander and N. Cunningham, "Beneficiated Solid Waste Cubettes as Salvage Fuel for Steam Generation," *Proceedings of the 1972 National Incinerator Conference* (American Society of Mechanical Engineers, 1972).

[44] *Summary Report of Solid Waste Processing Facilities* (American Iron and Steel Institute, 1978).

Table 4
Ames, IA, Fact Sheet

Location:	Ames, Iowa		
Date:	January 1979		
Contact:	Mr. Arnold O. Chantland Director of Public Works City of Ames, Iowa Municipal Annex Ames, Iowa 50010 (515) 232-6210, x211	Owner:	City of Ames
Status:	Operational	Operator:	City of Ames
Capacity:	200 TPD input (50 TPH)		
Products:		% of Weight	
	Ferrous metal	7	
	Glass	0	
	Nonferrous metal	Trace	
	RDF	84	
Process Equipment:		Supplier:	
	Scale, receiving	Toledo	
	Shredder (2 horizontal)	American Pulverizer (1,000 HP; model 60 x 90)	
	Disc screen	Rader	
	Air classification (straight)	Rader (model 130)	
	Magnetic separation	Dings 60	
	Trommel	Combustion Power	
	Aluminum magnet	Combustion Power	
	Cyclone separator	Pneumatics System	
	Boilers (2)	Riley, Union Iron Works	
	Baghouse	Monsanto	
	Storage	Atlas (84 ft dia., 500 ton)	
Economics:			
	Processing plant	$4,116,526	
	Conveyors	164,388	
	Storage bins	551,292	
	Electrical work	314,020	
	Boiler modifications	179,988	
	Land	108,068	
	Dust control system	403,417	
	Engineering	376,896	
	Start-up costs	486,405	
		$6,700,000	
	Operating cost:	$11.26/ton	
	Revenues:	$7.82/ton–fuel value $3.15/ton–recovered materials $1.00/commercial truck load $0.50/automobile load	

munities. The waste is delivered to a tipping floor after it is weighed and taken by front-end loader to a primary shredder. The feedstock is then screened, passed through a magnetic separator for the removal of ferrous material, and passed to a secondary shredder and through an air classifier from which it is pneumatically conveyed approximately 3/4 mile to an atlas-type fuel storage bin. The material is extracted from the bin on demand and fired in two spreader stoker-equipped boilers rated at 95,000 and 125,000 lb of steam per hour, respectively. A third boiler, designed to suspension-fire coal, has been tested, using the light shredded feedstock (or fluff RDF) produced from the plant. The tipping floor is approximately 100 x 160 ft. It has one entrance and exit for contract and commercial haulers and another for individuals hauling their trash to the plant. The total storage capacity of the tipping floor is approximately 350 tons of raw refuse. The

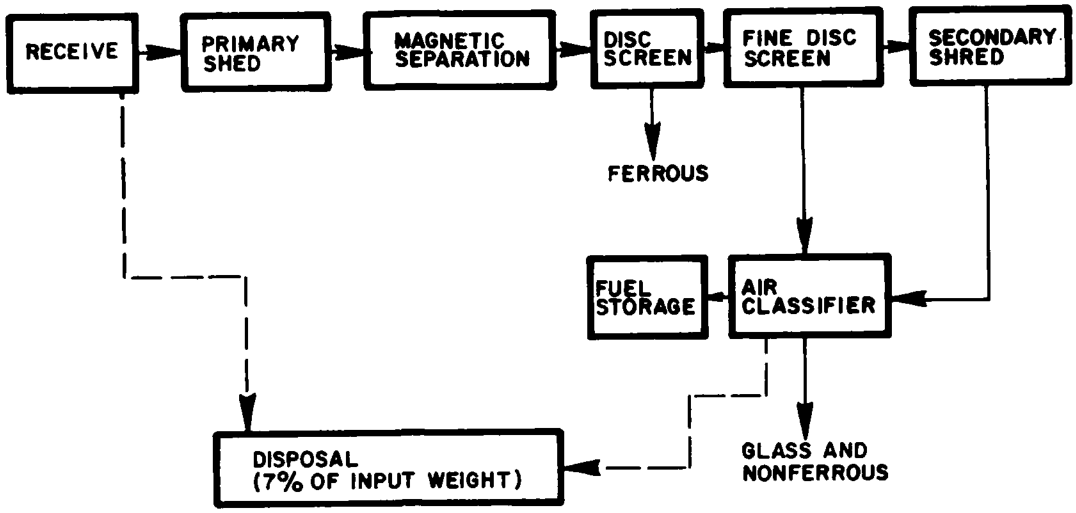


Figure 2. Process description of Ames, IA, plant.

process area is a multilevel process area made of reinforced concrete and equipped with blowaway ceiling/roof panels in case of shredder explosion.

The atlas-type storage bin used in the Ames plant has a capacity of 550 tons of refuse-derived fuel. It is approximately 80 ft in diameter and has the general appearance of an inverted cone. The unloading system is a variable-speed, motor-driven bucket sweep and a drag conveyor. Four pneumatic conveying lines move the refuse-derived fuel from the atlas storage bin to the nearby plant which contains the boilers. The refuse-derived fuel is burned at approximately a 20 percent substitution ratio with coal.

Table 5 shows the shift in characteristics between the incoming raw refuse and the outgoing RDF from the Ames process plant between July and December 1977.[45] Table 5 shows the shift in relative position between cardboard and paper as there is process movement from raw refuse to RDF. Cardboard comprises 16 percent of the incoming raw refuse, but 20 percent of the RDF from the plant. Paper comprises 35 percent by weight of the incoming raw refuse, but 33 percent of the RDF from the plant. In Table 5, the line item entitled "Miscellaneous" represents a large amount of the inorganic, incombustible material. This material comprises 20 percent by weight of the incoming raw refuse. In contrast, it comprises 23 percent of the RDF coming from the plant; i.e., the RDF produced by the Ames plant and fired in nearby boiler consists of at least 23 percent by weight of incombustible material, plus the weight percentage for glass, ferrous metal, and nonferrous metal, leaving approximately 28.5 percent of the RDF product as ash or residue. This is removed from the using boiler plant for disposal.

Table 5
Average Ames Solid Waste Classification by Weight, July-December 1977

(From *Energy From a Wasted Resource: The Ames Experience* [City of Ames, IA, 1978]. Reprinted with permission.)

Constituent	Incoming Raw Refuse (%)	RDF From Plant (%)
Cardboard	16	20
Paper	35	33
Plastics	4	5
Wood	6	8
Glass	8	4
Ferrous Metal	3	0.5
Nonferrous Metal	0.2	1
Natural Organics	5	3
Cloth	1.5	1.6
Tar	1	0.6
Miscellaneous (sand, grit, rock, dust, etc.)	20	23

Ames has carefully monitored equipment downtime and electrical consumption. The following is a typical

[45] *Energy From a Wasted Resource: The Ames Experience* (City of Ames, IA, 1978); "Experimental Diagnostics in Combustion of Solids," *Progress in Astronautics and Aeronautics*, Vol 63 (1978).

distribution of process plant downtime:[46] the shredder consumes 20 percent of the total plant downtime, while the air-density separators and conveyors consume 70 percent; the remaining 10 percent downtime is due to malfunction of the ferrous removal system, the non-ferrous removal system, and equipment on the tipping floor. A typical distribution of electrical power consumption is as follows: the primary shredder, which is a 1000-HP American pulverizer horizontal-shaft hammermill, consumes 11 percent; the secondary shredder, a similar unit, consumes 19 percent; the refuse-derived fuel storage bin material handling and conveying system consumes 18 percent; the remaining consumption by equipment is attributed to the air-density separator blower (7 percent) and the pneumatic conveying system (6 percent). Thirty-nine percent of the electric power consumption at Ames is attributed to indirect process plant consumption, which includes heating, ventilating, and air conditioning; lighting; miscellaneous belt conveyors; a special wood chipper; a paper bailer; and other auxiliary and ancillary equipment. At the time CERL personnel visited this plant (January 1979), Rader Pneumatic Corporation was installing disc screens between the primary shredder and magnetic separator and between the magnetic separator and the air classifier. These screens were to reduce secondary shredder maintenance and improve air classifier performance as well as reduce the amount of inorganic, incombustible materials in the refuse-derived fuel. Plant personnel will be carefully monitoring their experience with the disc screens and publishing data regularly.

[46] *Energy From a Wasted Resource: The Ames Experience* (City of Ames, IA, 1978); "Experimental Diagnostics in Combustion of Solids," *Progress in Astronautics and Aeronautics*, Vol 63 (1978).

East Baltimore County, Maryland

This facility (see Table 6 and Figure 3) is partially

Table 6
Baltimore, MD, Fact Sheet

Location:	Baltimore County (East), Maryland		
Date:	January 1979		
Contact:	Mr. Carl Schultz Plant Supervisor Maryland Environmental Services (MES) State Office Building Annapolis Maryland 21401 (301) 269-3357	Owner:	Baltimore County and MES
Status:	Partially operational	Operator:	Teledyne International
Capacity:	2000 TPD input; currently processing 600-700 TPD		
Products:		% of Weight:	
	Ferrous	5	
	Aluminum	0.25	
	Glass	7-8	
	RDF	55	
Process Equipment:		Supplier:	
	Scale	Toledo	
	Shredder, primary (2 horizontal)	Tracor-Marksman Toshiba (1000 HP, 55 TPH)	
	Magnetic separation (2)	Dings	
	Air classification (2)	N.C.R.R. (modified)	
	Screening	N.C.R.R. 3-stage trommeling	
	Shredder, secondary (horizontal)	Gruendler (1000 HP)	
	Compactor	Heil-HT 65	
	Aluminum separation	Carpco	
	Baghouse	Griffin Engineering	
	(Note: No boiler data available.)		
Economics:			
	Construction costs:	$8,400,000 processing plant $1,000,000 transfer station $600,000 market development	
	Operational cost and revenues are not available.		

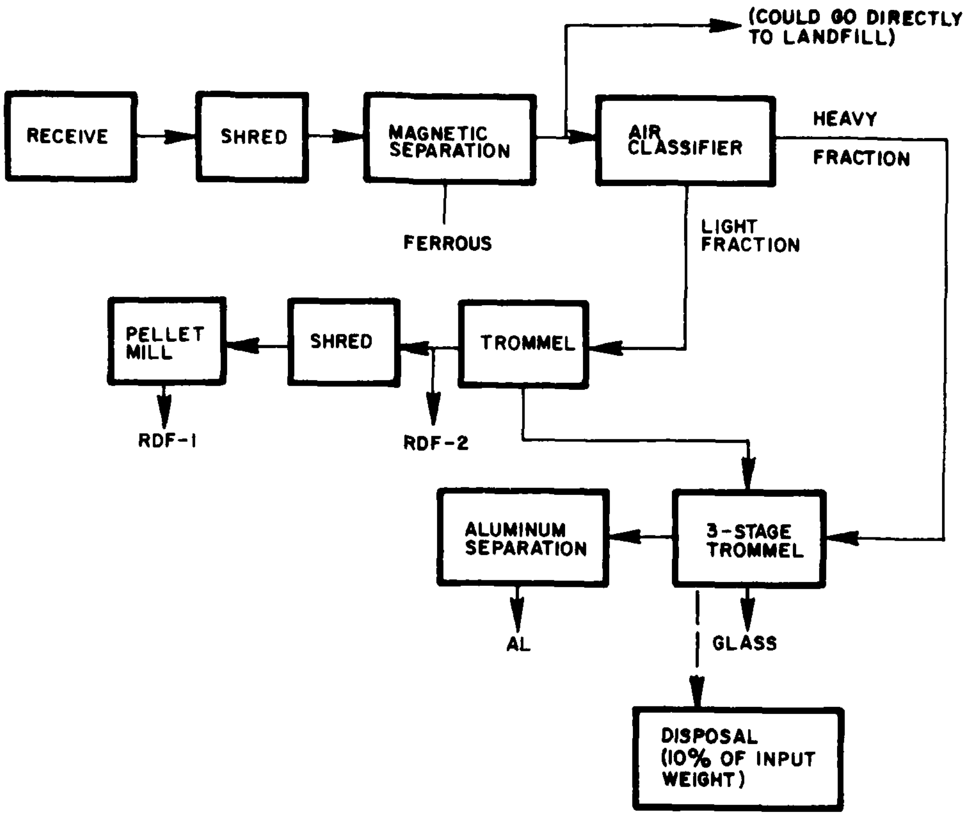


Figure 3. Process description of Baltimore, MD, plant.

operational. It was designed to process approximately 2000 tons per day of delivered as-received solid waste. Currently, however, it is processing a maximum of 600 tons per day. The process flow of the plant differs significantly from that of the Ames plant. In the Baltimore plant, the first two stages are the same—shredding and separation of magnetic materials. However, directly after the magnetic separator, the feedstock goes through an air classifier, to a trommel screen, then through a secondary shredder, and finally to a pellet mill. Material coming from the bottom of the air classifier and the bottom of the trommel is screened again through a three-stage trommel screen to remove material composed principally of glass. Those heavies go to a special high-inductive magnetic aluminum separator for aluminum recovery. No mass balance on this process is available. The current estimated cost of this plant is $8.4 million, which is equivalent to an investment cost of $4200 per ton per day capacity. The operator of the plant, Teledyne International, estimates that 55 percent of the delivered mass will become refuse-derived fuel pellets.

The plant staffs approximately 50 personnel per shift and currently operates one shift of 8 to 10 hours per day. The primary shredder is a Tracor-Marksman Toshiba, which is a 1000-HP horizontal shaft-hammermill. To date, only a few problems besides the usual startup difficulties have been experiened with the shredder. Originally, this plant used a prototype air classifier made by the National Center for Resource Recovery; however, the machine never worked and has been completely modified by the plant operators. Now a straight vertical-tube air classifier with strategically placed baffles is used.

This plant has produced only a small amount of DRDF, principally for EPA-sponsored burn tests and U.S. Air Force tests. Most of the shredded material is diverted from the process and sent to landfill. Conversations with plant personnel revealed they do not know the heating value of the DRDF produced and that there have been some problems with storing the pellets. This has been attributed to the moisture content of the pellets, which are estimated to be 20 percent moisture and 7 to 12 percent ash. The pellets are stockpiled in the open air and a crust tends to form over the top, which makes their handling by front-end loader

or bobcat somewhat difficult. Overall, there have been very few problems in handling the pellets, and personnel are hopeful that there will be no difficulties during normal plant operation.

The greatest problem with this facility has been explosions in the shredders. Personnel have attempted to alleviate much of this problem by accepting only residential waste, since it contains fewer combustibles typically found in industrial wastes such as paints and aerosols.

Bridgeport, Connecticut

This facility (see Table 7 and Figure 4), owned by the Connecticut Resource Recovery Authority and operated by Waste Management Corporation of Oak Brook, IL, is currently in shakedown status. The plant is designed to process approximately 2000 tons per day of received as-discarded solid waste. The plant plans to produce Eco-Fuel, a finely pulverized material known in the field as dust refuse-derived fuel. According to planning calculations, between 45 and 52 percent of the input material will become dust RDF. This type of fuel

Table 7
Bridgeport, CT, Fact Sheet

Location:	Bridgeport, Connecticut		
Date:	January 1979		
Contact:	Mr. Richard Valonino Project Manager Combustion Equipment Associates, Inc. (CEA)* 555 Madison Avenue New York, New York 10022 (212) 980-3700	Owner:	Connecticut Resource Recovery Authority (CRRA)
Status:	Shakedown	Operator:	Waste Management
Capacity:	1800-2000 TPD (input)		
Products:		% of Weight:	
	Eco-Fuel® II	45-52	
	Ferrous	5-7	
	Aluminum	0.2	
	Glass	5	
	Disposals	5-7	
Process Equipment:+		Supplier:	
	Scale	Howard Richardson	
	Infeed conveyors	Wallace	
	Flail mill	Southern	
	Shredder (horizontal)	American Pulverizer and a Texas Longhorn	
	Magnetic separation	Eriez	
	Air classification	CEA (Carter-Day)	
	Aluminum separation	Oxy	
	Trommel	CEA (Carter-Day)	
	Ball mill	N.A.	
	Storage silos	CEA (Carter-Day)	
	Glass recovery	Oxy	
	Baghouse	CEA (Carter-Day)	
	Boilers	Babcock-Wilcox	
	(Note: No boiler nominal capacity available.)		
Economics:			
	Construction costs:	$53,000,000	
	Tipping fee:	$12.96/ton + escalations†	
	No other operating costs or revenues are available.		

*Joint venture between CEA and Occidental Research and Development Co. (Oxy).

+Identical fuel processing lines each rated at 75 TPH.

†$12.94/ton plus escalations based on the Consumer Price Index, using August 1974 as the base. Current tipping fee: $14.21.

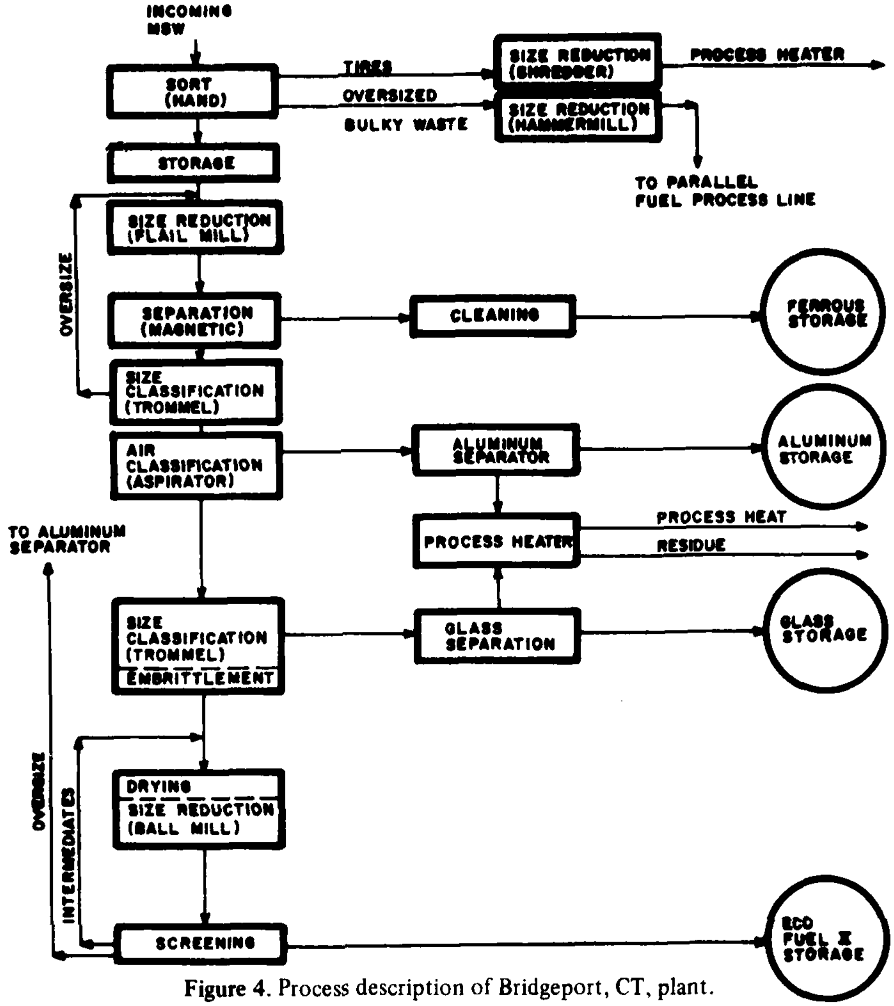


Figure 4. Process description of Bridgeport, CT, plant.

is produced from fluff RDF by adding embrittling and pulverizing steps to the process flow. Of interest in this investigation is the performance and sequencing of unit operations to produce a fluff RDF which, for stoker firing, could then pass through a pellet mill to form DRDF.

As indicated in the process flow diagram in Figure 4, delivered solid waste first passes through a flail mill, and then through a magnetic separator, a trommel screen, and an air classifier. Oversized waste and tires are handled by other shredders. The plant provides for the removal of ferrous material, aluminum, and glass for potential recycling. The primary shredder is an American Pulverizer, 300-HP, horizontal-shaft hammermill. The plant eventually plans to add additional shredding capacity. Current shredding capability is limited to a capacity of 50 tons per hour. The air classifier is a special design made by Combustion Engineering Associates and operates on a double-venturi principle. Like many other recently designed refuse-derived fuel processing facilities, unprocessed solid waste is handled by metal-pan conveyor. All other conveyors in this plant are the rubber-belt type. Plant personnel have indicated that there are some problems at the turning point of the conveyors, including spillage of material and emission of high volumes of dust. The Eco-Fuel is stored in conical silos with vibrating bottoms manufactured by Combustion Engineering Associates. So far, plant personnel have not noted any storage or handling problems with the material.

However, personnel have been concerned with problems of wear on the primary shredder. This wear is probably caused by the presence of highly abrasive materials which accelerate wear on the hammer tips of the flail mill. Plant personnel have also noticed some problems with adverse materials, such as rags, panty

hose, cable, sheet plastic, and rugs, entering the primary shredder. Consequently, an initial operation is manually sorting out adverse materials which may damage downstream equipment.

The labor requirement at this facility appears to be quite intensive. The facility operates three shifts per day, with 54 personnel on the first shift, 45 on the second, and 28 on the third. During actual operations, the plant will be run 16 to 20 hours per day, with the remaining time devoted to maintenance. Currently, third-shift activities are 80 percent maintenance and repair duties.

Chicago, Illinois

This facility (see Table 8 and Figure 5), owned and operated by the City of Chicago, is currently in the shakedown status. It is designed to produce fluff RDF for use in local utility boilers rated at 165,000 lb per hour. According to planning calculations, the plant will receive up to 2000 tons per day of as-discarded solid waste from the city. Approximately 70 percent of this input material will become a light, unconsolidated fluff RDF and will be suspension-fired in the boilers.

The unit operations in this plant (see Figure 5) compare to those of the plants discussed in the previous

Table 8
Chicago, IL, Fact Sheet

Location:	Chicago, Illinois–Southwest Supplementary Fuel Processing Facility		
Date:	January 1979		
Contact:	Mr. Emil Nigro Streets and Sanitation Department City Hall Chicago, Illinois 60602 (312) 744-5038	Owner:	City of Chicago
Status:	Shakedown	Operator:	City of Chicago
Capacity:	1000 TPD (each line) (80 TPH each line; input)		
Products:		% of Weight:	
	Ferrous	8.6	
	RDF	70	
Process Equipment:*		Supplier:	
	Pan conveyor	J. W. Greer	
	Shredder (primary; horizontal)	Williams (1000 HP; 80 TPD; model 6100)	
	Air classification	Triple/S Dynamics	
	Magnetic separation	Stearns	
	Shredder (secondary)	Carborundum (750 HP; 60 TPH)	
	Storage silo	Atlas	
	Baghouse	CEA (Carter-Day)	
	Boilers (2)	N.A.	
	(Note: RDF fired in two boilers at a nominal rate of 165,000 pounds of steam per hour each.)		
Economics:			
	Processing plant construction	$13,351,000	
	Power plant facilities	4,500,000	
	Engineering	1,000,000	
		$18,851,000	
	Plant operating costs (estimated)+	$6.70/ton	
	– Labor	$3.14/ton	
	– Electrical power	1.36	
	– Maintenance	1.36	
	– Utilities	0.33	
	– Residual disposal	0.50	
	No revenue data available.		

*Identical processing lines.

+Based on 1000 TPD capacity.

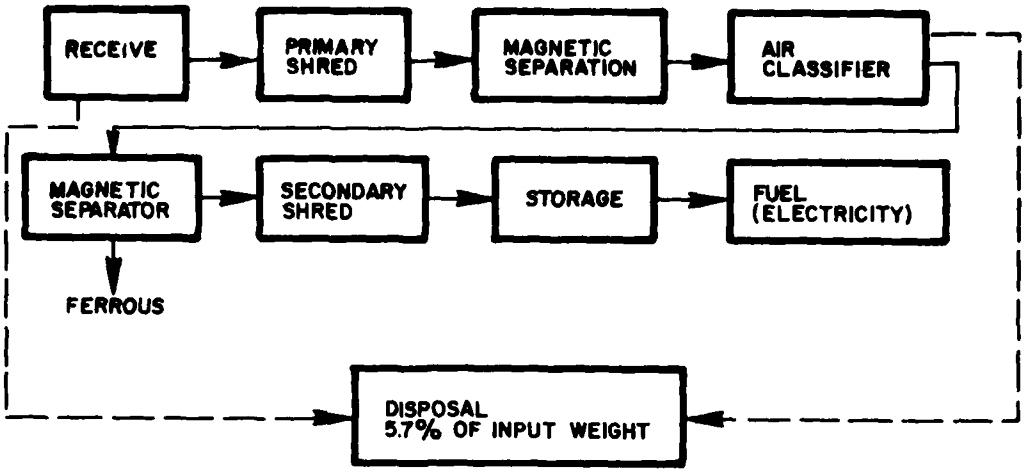


Figure 5. Process description of Chicago, IL, plant.

sections. Delivered solid waste first passes through a primary shredder, then a magnetic separator, through an air classifier, to a secondary magnetic separator, to a secondary shredder, and then to temporary storage. It is withdrawn from temporary storage on demand to fire utility boilers. The primary shredder is a Williams horizontal-shaft hammermill rated at approximately 1000 HP. The hammermill has 40 hammers and reversible hammer belts, so that both sides of the hammers can be used. The secondary shredders, made by Carborundum, are vertical-shaft hammermills rated nominally at 750 HP. The primary shredder has a capacity of 80 tons per hour, while the secondary shredder has a capacity of 60 tons per hour. Plant personnel have experienced many problems with the shredders, both of which have been redesigned in the field many times. The major modifications have been placing shear and breaker bars inside the shredders to emphasize the shearing process rather than the grinding process. This will hopefully help eliminate jamming and packing of waste material within the shredders.

The air classifier, manufactured by Triple/S Dynamics of Texas, has been redesigned in the field numerous times. The major modification has been the addition of guide vanes to smooth the flow of material through them.

Like other recently designed refuse-derived fuel processing facilities, this plant uses metal pan conveyors to handle incoming solid waste. Nearly all other conveyors in the plant are the rubber-belt type.

The plant has experienced only minor problems in storing the fluff RDF, principally because it is shipped out the same day it is processed. Plant personnel have noted that after it is stored in the nearby atlas bins for approximately 1 week, the refuse becomes glued together from the internal heat. This causes severe bridging problems, and plant personnel have often been forced to remove the material from the bins manually.

Approximately 70 percent of the input mass becomes refuse-derived fuel. Although this is planning calculation, personnel feel that this amount will be derived during actual operations. Only residential refuse is accepted at this plant, and it is estimated that the heating value of the refuse-derived fuel will be approximately 6000 Btu/lb.

So far, the most severe problem has been that the refuse wears out most of the major equipment very quickly; this has been attributed to the very abrasive properties of the delivered refuse. For example, hammers in the shredders wear out very rapidly. Plant personnel are currently experimenting with various ways to solve this problem. The abrasiveness of the refuse also blasts holes in the pneumatic lines, especially at the turns; however, this problem is not new. Such problems were experienced several years ago when fluff RDF was produced and fired in a St. Louis utility boiler under an EPA demonstration grant. Personnel in Chicago have attempted to solve this problem by placing baffles near turns in the lines; however, severe wear continues to be noted even in straight sections of the lines.

Like other solid waste processing facilities, the Chicago plant is comparatively labor-intense. Current plans are to operate the refuse-derived fuel production

facility for one shift per day, 5 days a week, with some overtime. The total labor requirement, including maintenance and routine repair, is 48 persons per shift.

Brockton, Massachusetts

Like the Bridgeport, CT, plant, the Brockton, MA, plant (see Table 9) is designed to produce Eco-Fuel, also known as dust RDF, a finely pulverized fuel suitable for suspension firing in utility boilers. As with the Bridgeport plant, the performance of the equipment used to process solid waste into a light fluff material which can be pelletized for military application is of interest.

This plant is owned by the East Bridgewater Association and operated by Combustion Equipment Associates. It receives approximately 800 tons per day of solid waste generated within the municipality. The plant has been operational for several years. Between 50 and 52 percent of the input mass becomes refuse-derived fuel. There is removal and some salvage of recovered ferrous materials (see Table 9).

At the time of this study, plant personnel were reluctant to discuss the technical details of the production process, possibly because the inquiries closely followed a plant explosion which is currently being investigated. Although no data can be offered about this process at this time, it may generally be assumed that the technical attributes of refuse-derived fuel production at the Bridgewater facility resemble those at Bridgeport, CT.

Table 9
Brockton, MA, Fact Sheet

Location:	East Bridgewater (Brockton), Massachusetts		
Date:	January 1979		
Contact:	Mr. Richard A. Volonino Combustion Equipment Associates, Inc. (CEA) 555 Madison Avenue New York, New York 10022 (212) 980-3700	Owner:	East Bridgewater Association 234 Thatcher Street East Bridgewater, Mass. (617) 588-2260
Status:	Operational	Operator:	CEA
Capacity:	800 TPD (input)		
Products:		% of Weight:	
	Eco-Fuel® II	50-52	
	Ferrous	5-6	
	Aluminum	N.A.	
	Glass	N.A.	
	Disposal	5-7	
Process Equipment:		Supplier:	
	Scale	Howard Richardson	
	Infeed conveyors	Wallace	
	Flail mill	Southern	
	Shredder (horizontal)	American Pulverizer and a Texas Longhorn	
	Magnetic separation	Eriez	
	Air classification	CEA (Carter-Day)	
	Aluminum separation	Oxy	
	Trommel	Rotex and Gruendler	
	Ball mill	N.A.	
	Storage silos	CEA (Carter-Day)	
	Glass recovery	Oxy	
	Baghouse	CEA (Carter-Day)	
	Boilers	Babcock-Wilcox	
	(Note: no boiler nominal capacity available.)		
Economics:			
	Construction cost (estimate)	\$10,000,000-\$12,000,000	
	No operational cost or revenue data are available.		
Process Description:			
	See Figure 4.		

Hempstead, New York

The Hempstead solid waste processing facility (see Table 10 and Figure 6) is owned by Hempstead Resource Recovery, Inc., and operated by Black-Clawson Company of Middletown, Ohio. This plant is a scale-up of Black-Clawson's prototype refuse-derived fuel production facility which operated until 1979 in Franklin, OH. The Franklin plant received approximately 150 tons per day of solid waste from nearby municipalities. A major feature of the Franklin plant was the use of hydrapulping. The Black-Clawson Hydrapulper is essentially a wet shredding process, which is believed to reduce the possibility of explosion from dust, which is a problem in dry shredding operations.

The Hempstead facility is designed for a maximum production capacity of 2000 tons per day, and is currently receiving 800 tons per day. The Franklin plant produced pelleted refuse-derived fuel; the Hempstead plant will produce a refuse-derived fuel that will be fired in a nearby utility boiler rated at 400,000 lb of steam per hour.

Hempstead personnel are optimistic that their process will reach nominal operation at design capacity within 12 months. Only two problems have been noted. The first problem is odor, which also plagued the Franklin plant. Plant personnel hope to control this problem by sealing equipment and providing proper plant ventilation. The second problem is controlling ash, which accelerates wear of process equipment. This is not unlike the ash and abrasion problems encountered in other solid waste processing facilities.

The Hempstead plant is partially operational. Approximately 120 persons work in around-the-clock shifts to shake down and align the equipment. The heating value of the refuse-derived fuel is expected to be approximately 4000 Btu/lb.

The production flow (see Figure 6) begins with primary shredding in the patented Black-Clawson Hydrapulper, followed by the magnetic removal of ferrous materials. The shredded material is saturated with water, which must be removed by a roll press before the product can be used effectively as a fuel. No operational data for this facility are currently available. However, CERL personnel who visited the Franklin plant observed no major problems with the handling and wet shredding of the delivered solid waste.

The unit operation at the Franklin plant which was of greatest concern was the glass recovery unit, which was supposed to color-sort recovered glass from various points in the production process. The glass recovery system appeared to be very labor-intensive and was not operational when observed by CERL personnel. According to plant personnel, the glass recovery unit was operated infrequently, partly because only one operator was trained to operate it.

Lane County, Oregon

This facility (see Table 11 and Figure 7), owned by Lane County and operated by Western Waste, Inc., is designed to receive up to 500 tons per day of solid waste generated in regional municipalities. According to planning calculations, approximately 45 percent of the received material will appear as light fluff RDF for suspension firing in a nearby boiler.

The sequence of unit operations of interest in this plant was the production of the light fraction. Received solid waste passes through a primary shredder, a screen, an air classifier, a secondary shredder, and then goes to storage. Refuse-derived fuel is withdrawn from storage on demand.

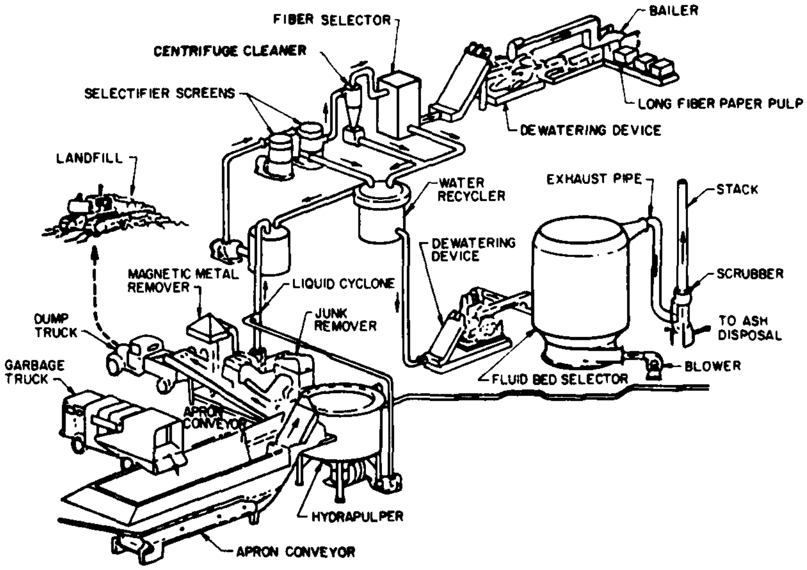
The primary shredder at the Lane County facility is an Allis-Chalmers horizontal-shaft hammermill rated at 1000 HP, which has a processing capacity of approximately 62 tons per hour. The air classifier is an Allis-Chalmers dual-vortex system. This plant accepts all commercial, industrial, and residential waste generated in the nearby communities. Plant operators encourage private haulers to separate large metal objects (bypass wastes) from other refuse delivered to the plant. Removing such adverse objects will probably improve equipment performance. According to plant personnel, the primary shredder, the air classifier, and the secondary shredder have operated rather well, and the problems that have been experienced are those common to all shakedown operations. However, it must be noted that this plant rarely operates at full capacity.

Delivered waste is handled by a steel pan conveyor, which elevates the delivered solid waste approximately 138 degrees to the primary shredder feed inlet. The conveyor is designed to accommodate 5 tons of solid waste at a time, and its elevation angle, cleats, and guillotine for load leveling provide uniform flow to the shredder. Other conveyors are high-speed belt conveyors, which have shown only minor operational problems.

No data regarding boiler performance on the refuse-derived fuel were available. According to plant person-

Table 10
Hempstead, NY, Fact Sheet

Location:	Hempstead, New York		
Date:	January 1979		
Contact:	Mr. William Landman Commissioner of Sanitation 1600 Merrick Road Merrick, New York 15566 (516) 378-4210	Owner:	Hempstead Resource Recovery
Status:	Partially operational	Operator:	Black-Clawson
Capacity:	2000 TPD: currently processing 800 TPD (input)		
Products:		% of Weight:	
	Ferrous	6.0-7.0	
	Glass	4.0	
	Aluminum	0.8	
	RDF (wet-hydrapulper)	55	
	Disposal	14	
	(Ncte: boiler rated at 400,000 pounds of steam per hour.)		
Equipment:		Supplier:	
	Black-Clawson Hydrapulper Recovery System	Black-Clawson	
Economics:			
	Construction cost:	$73,000,000	
	Operation cost:	$15.00/ton	
	No revenue data available.		



BLACK-CLAWSON MATERIAL RECOVERY PROCESS

Figure 6. Process description of Hempstead, NY, plant. (From *Solid Waste Management, Technology Assessment* [General Electric Co., 1975]. Reprinted with permission.)

Table 11
Lane County, OR, Fact Sheet

Location:	Lane County, Oregon		
Date:	January 1979		
Contact:	Mr. Mike Turner Administrative Assistant Lane County Department of Environmental Management 135 East 6th Street Eugene, Oregon 97401 (503) 687-4119	Owner:	Lane County
Status:	Operational	Operator:	Western Waste
Capacity:	500 TPD (input)		
Products:		% of Weight:	
	Ferrous	5	
	RDF	45	
Equipment:		Supplier:	
	Shredder (primary; horizontal)	Allis-Chalmers (1000 HP)	
	Magnetic separation	N.A.	
	Air classification	Allis-Chalmers	
	Screen	Allis-Chalmers	
	Storage	Peerless Silo	
	Shredder (secondary; horizontal)	Allis-Chalmers (1000 HP)	
	(Note: no boiler data available.)		
Economics:			
	Construction cost:	$2,124,000	
	No operational costs or revenues are available.		

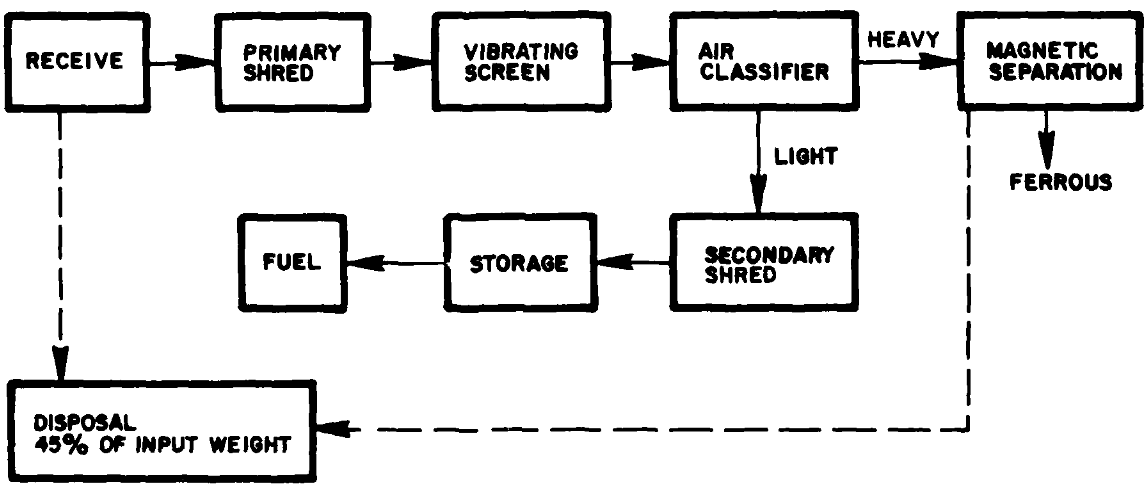


Figure 7. Process description of Lane County, OR, plant.

nel, the average heating value of the refuse-derived fuel ground to 2-in. top size is 5000 Btu/lb.

Several problems have been revealed during the first years of this facility's operation. Refuse-derived fuel was originally stored in a Peerless bin, a silo commonly used to store wood waste in the Pacific Northwest. However, it did not work well for refuse-derived fuel, because as the fuel was discharged from the storage bin, the large exchange of air caused a litter problem. Plant personnel have now totally inclosed a storage bin with a movable baffle which keeps the diameter at the bottom of the bin larger than at the top. Therefore, there is very limited settling and caking of the refuse-derived fuel.

So far, there have been no severe shredder explosions. Nevertheless, the plant is designed so that the force from such explosions will be diverted upward. The final problem has been associated with burnout of screw conveyor motors. Plant personnel replaced the original motors with motors having greater horsepower, anticipating that this would solve the problem. However, just after the replacement, the larger motors tended to overdrive the augers which blew out the air locks. This problem has now been solved.

The labor requirements anticipated for full-scale operations include four laborers and one supervisor. This number excludes the Lane County Landfill employees who will have assignments at both locations when the facility is running at capacity.

Madison, Wisconsin

The Madison, WI, solid waste size reduction facility (see Table 12 and Figure 8) is one of the oldest in the United States. However, it is unique because it is among the more well-documented solid waste milling and disposal operations.[47] The operation is currently a shred and spread type of landfill disposal system. As indicated in Figure 8, the process flow resembles those discussed previously in this report. Solid waste is received, and then passes through a primary shredder, a magnetic separator, a secondary shredder, and then to storage in large trucks. The material is then taken to the landfill and disposed without cover. Plant personnel estimate that the average heating value of this fluff RDF is 5000 Btu/lb. The City of Madison is currently searching for a user of the light refuse-derived fuel produced by this facility.

[47] *Solid Waste Milling and Disposal on Land Without Cover,* two volumes (City of Madison, WI, 1974).

Table 12
Madison, WI, Fact Sheet

Location:	Madison, Wisconsin		
Date:	January 1979		
Contact:	Mr. Ken Bruner Plant Manager Public Works Department Madison, Wisconsin 53709 (608) 266-4911	Owner:	City of Madison
Status:	Partially operational	Operator:	City of Madison
Capacity:	400-500 TPD; currently processing 250 TPD (input)		
Products:		% of Weight:	
	Ferrous	5	
	RDF	50	
Process Equipment:		Supplier:	
	Scale	Cream City	
	Shredder (primary)	Universal Welding	
	Magnetic separation	Madison Magnetic Corp.	
	Air classification	N.A.	
	Shredder (secondary)	Tollemesh	
	Baghouse	Mac Manufacturing	
	Note: Boiler data unavailable.		
Economics:			
	Construction cost:	$2,500,000	
	No operational costs or revenues are available.		

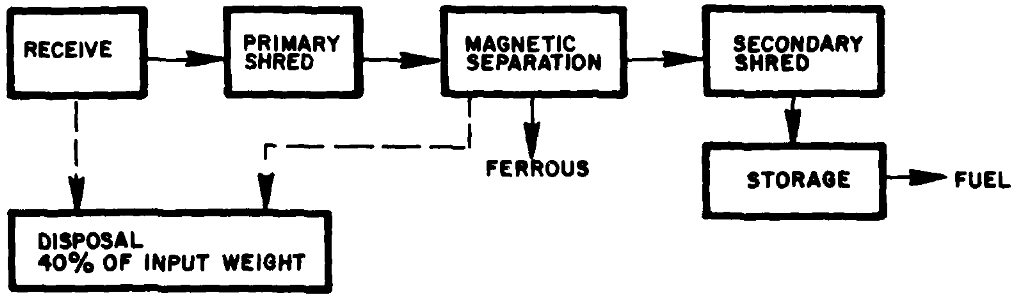


Figure 8. Process description of Madison, WI, plant.

This plant has been operating since 1967, and in 1978 it was operating at approximately 50 percent capacity. The plant employs 11 persons per shift and operates two shifts per day. Solid waste is delivered by garbage truck and dumped in a live-bottom receiving pit. The conveyors are cleated steel pan conveyors. The primary shredder is a flail mill manufactured by Universal Welding Corporation. The secondary shredder is a vertical-shaft hammermill manufactured by Heil. The plant uses a drum-type magnetic conveyor. It does not have an air classifier for removing heavy materials from the shredded feedstock.

This project began as a demonstration sponsored by the U.S. Environmental Protection Agency to investigate the concept of milling solid waste for landfill disposal without applying daily cover. The project was intended to gather data on the operation and cost of milling equipment, the use of milled solid waste in a landfill, and the characteristics of milled solid waste. The original plant included two hammermills. The first was a Gondard horizontal-shaft hammermill, which was equipped with forty-eight 15-lb swinging hammers on four shafts. The hammers were driven at 1150 rpm by a 150-HP motor, and the mill had a discharge grate to allow control of the size of the material leaving the assembly. The second hammermill was a vertical-shaft, ballistic-rejection Tollemache, installed in 1969. The rotor is driven at 1350 rpm by a 200-HP motor.

Many important conclusions regarding the milling of solid waste were reached under this demonstration project. The Gondard hammermill had a capacity of approximately 9 tons per hour with a 5-in. discharge grate, and the Tollemache hammermill had a capacity of 14 tons per hour with a 34-hammer pattern. On a dry weight basis, between 80 and 90 percent of the particles produced by both mills passed through a 2-in. screen. The demonstration showed that the Gondard mill used nearly as much electrical power as the Tollemache mill, while producing only about 60 percent as much milled product. Thus, it was found that the vertical-shaft hammermill was more efficient than the horizontal-shaft hammermill from an electrical power standpoint.

Most of the early operational problems at the Madison facility were associated with conveying refuse to the mills and carrying milled refuse to the landfill. The shredders were fed by steeply inclined feed conveyors, and material tended to jam, bridge, or simply fall off. Early operating adjustments solved these problems. The demonstration indicated that residential and light commercial refuse could be shredded in either type of hammermill without extensive presorting, with minimal manual removal of unmillables and negligible downtime caused by adverse materials stopping the mill. From this experience, it has been recommended that horizontal- rather than vertical-shaft hammermills be used in solid waste shredding operations. In fact, most operating processes reviewed in this investigation preferred the horizontal-shaft hammermill configuration, particularly because it allows acute size control of the discharged material through modulation of the discharge grate size. CERL personnel have witnessed similar success with horizontal-shaft hammermills in other locations, such as Charleston, SC.[48]

[48]Personal communication between Mr. S. Hathaway (CERL), and Public Health Department officials, City of Charleston, Charleston, SC (April 1975).

Other major conclusions relate to the environmental consequences of landfilling shredded solid waste with no cover. Shredded refuse has been left in the landfill at Madison for up to 10 years, and there have been no complaints about odors, unsightliness, blowing litter, rodents, or insects. This experience indicates that the operational quality of this type of landfill is superior to that of sanitary landfill operations at Madison with respect to travel over the fill and at the face of the fill, dust, tracking of trucks on highways, appearance during operating hours, and maintaining a uniformly high level of operation during cold and wet weather. Experience at Madison and specific testing have indicated that there is less fire hazard with milled than with unprocessed uncovered waste in a landfill. Moreover, rats cannot survive on properly milled refuse containing up to 20 percent wet garbage on a wet-weight basis. This experience indicated that flies probably can breed in freshly milled refuse, but not after the refuse has aged several months. Madison's test with the Gondard mill showed that nearly all fly maggots passing through the mill during normal operation were killed. Fly counts and operating experience at Madison have indicated that there was no fly nuisance problem associated with the milled refuse.

Compaction of cover soil as well as production of methane and carbon dioxide by underlying refuse created poor aeration conditions for tree roots, which led to a high mortality rate of trees planted on milled and unprocessed refuse cells after 2 years. White Ash and Crab were the most successful of the tree species planted, because they developed an effective lateral root system in the densely compacted cover soil. The actual refuse density of milled refuse on a wet-weight basis was found to be approximately 27 percent greater than that of unprocessed refuse, given equal compaction. Under the same conditions, the effective density of milled refuse was calculated to be 35 percent greater than that of unprocessed refuse.

Leachate was produced faster in milled uncovered cells than in covered cells of either milled or unprocessed refuse. In the absence of cover, milled refuse developed a relatively mature degradation pattern and thus lowered the organic pollution load leaving the refuse leachate. Before a mature degradation condition developed in milled refuse, large quantities of organics were leached from the material. Under this multiyear demonstration, the covered unprocessed refuse cells never produced organics at as high a rate as the milled cells during the initial stages of decomposition. However, the unprocessed cells continued to produce organics at a fairly consistent rate throughout the duration of the project. Thus, it was concluded that the milled refuse cells could be characterized as producing more leachate contaminants than the unprocessed refuse cells during the initial stages of decomposition, but fewer during the later stages of decomposition.

Madison's first evaluation of the 5-in. Gondard mill in mid-1968 indicated a per ton cost of $7.75 (including process and hauling costs but excluding landfilling costs). When this figure was adjusted to exclude factors related solely to the experimental aspects of the operation, a comparable cost of $5.33 per ton became a reasonable estimate. During a similar evaluation of the Tollemache mill in 1970, a cost of $4.13 per ton was calculated for milling and hauling. For a two-mill, two-shift operation during the first 6 months of 1972, a milling cost of $3.90 per ton was determined, based on 23,317 tons milled. Another 48 cents per ton was added to this figure to cover compaction and hauling less than 1/2 mile to the landfill. The operating costs of landfilling for the first 6 months of 1972 were approximately $1 per ton for milled refuse and $3 per ton for unprocessed refuse, excluding any land and development cost.

Based on the findings of this demonstration, a cost of $3.11 per ton of milled refuse was projected for a two-shift, two Tollemache-mill operation. This figure included milling, hauling for less than 1/2 mile, and landfilling, and assumed a continuous supply of millable refuse. If this figure of $3.11 per ton in 1974 is escalated at 8 percent per year to its current value, the cost is $4.57 per ton for milled refuse. This is somewhat less than the cost of shredding and landfilling solid waste observed in Charleston, SC, in 1976, which was then approximately $5.90 per ton.[49]

The experience of this project indicates that considerable confidence can be associated with using the horizontal-shaft hammermill on a solid waste stream that is devoid of many adverse materials. However, shredder and hammermill wear is still a problem. As much as 4 hours per day is spent in routine maintenance and repair activities.

[49]Personal communication between Mr. S. Hathaway (CERL), and Public Health Department officials, City of Charleston, Charleston, SC (April 1975).

Milwaukee, Wisconsin

This facility (see Table 13 and Figure 9), which is owned and operated by Americology Corporation, is partially operational. It is designed to receive a maximum of 1600 tons per day of solid waste, and currently processes between 600 and 900 tons per day. Based on planning calculations, approximately 46 percent of the received solid waste will become fluff RDF.

In this process, received solid waste passes through a primary shredder, an air classifier, a magnetic separator, a secondary shredder, a screen, and then to storage. The refuse-derived fuel is withdrawn from storage on demand for firing in a nearby utility boiler to produce electricity. No boiler data are currently available. The process includes the removal and recycle of ferrous metals, glass, aluminum, and high-quality newsprint and cardboard.

Table 13
Milwaukee, WI, Fact Sheet

Location:	Milwaukee, Wisconsin		
Date:	January 1979		
Contact:	Dr. William Young Americology American Can Company American Lane Greenwich, Connecticut 06830 (203) 552-2568	Owner:	Americology; city owns site
Status:	Partially operational	Operator:	Americology
Capacity:	1600 TPD: currently processing between 600 and 900 TPD (input)		
Products:		% of Weight:	
	Ferrous	6.0	
	Glass	7.0	
	Aluminum	0.5	
	RDF	46	
	Papers (newsprint and cardboard)	7.0	
Process Equipment:*		Supplier:	
	Scale	Toledo	
	Shredder (primary; horizontal)	Williams (1000 HP)	
	Magnetic separation (belt)	Dings	
	Air classification (zig-zag)	Americology	
	Screen (2)	Rader and Triple/S Dynamics	
	Compactor	Heil	
	Shredder (secondary)	Heil	
	Baghouse	N.A.	
	Storage	Atlas	
	Note: No boiler data are available.		
Economics:			
	Construction cost	$18,000,000	
	Operating costs ($/ton)		
	Debt service	$7.90	
	Property tax	2.00	
	Fuel rebate	0.35	
	Revenues:		
	Tipping fee	$ 10.00⁺	
	Ferrous	30.00	
	Aluminum	300.00	
	Glass	2.00	
	RDF	($0.96/$10^6$ Btu)	

*Duplicate process lines.

⁺Adjusted to Consumer Price Index.

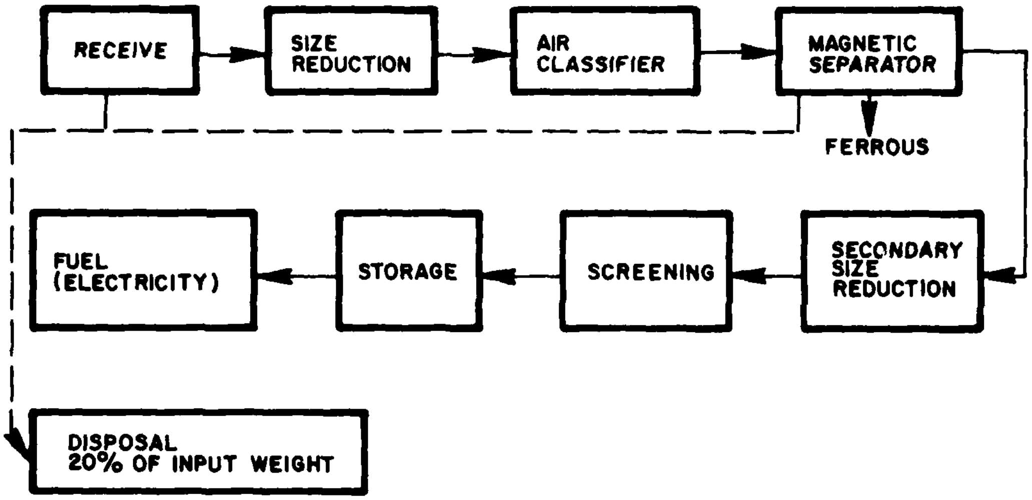


Figure 9. Process description of Milwaukee, WI, plant.

The primary shredder is a 1000-HP Williams horizontal-shaft hammermill. The air classifier is a three-story zigzag configuration made by Scientific Separators, Inc., and modified by the American Can Company. In the original facility design, all conveyors were the belt type. However, after startup, it was discovered that the majority of these conveyors were underdesigned, being too small and having inadequate working depth. Accordingly, nearly all of these conveyors have been either rehabilitated or replaced, and the plant has experienced no operating problems since. The heating value of the refuse-derived fuel is estimated to range between 5000 and 5200 Btu/lb. The fuel is stored in atlas bins at a location approximately 20 miles from the plant. The atlas bins have functioned very efficiently, according to plant personnel.

Although some operational problems have been experienced, the major problem at this facility has been equipment wear, particularly in the duct work and the pneumatic conveying lines. The plant is currently experimenting with different types of construction materials to reduce the rate of material wastage.

This process is relatively labor-intensive. The facility operates two 25-person shifts per day. The third shift is reserved entirely for equipment maintenance and repair.

Rochester, New York

This facility (see Table 14 and Figure 10), which is owned and operated by Eastman-Kodak Corporation, is currently operational. It is designed to receive approximately 500 tons per day of solid waste generated at the industrial plant.

Received solid waste is shredded, air-classified, and passed immediately to storage. The refuse-derived fuel is withdrawn from storage as required to feed a boiler rated at 77,000 lb per hour. (No boiler data are available.) The primary shredder is an Eidal vertical-shaft hammermill rated at 35 tons per hour processing capability for conventional refuse. In actual operation, it processes approximately 12 tons per hour. The air classifier was manufactured by Rader Numatics Incorporated. The original design was a vertical rectangular unit with a slight zigzag and movable baffles which controlled air current velocity. Since its original installation, the air classification has been modified several times to increase its efficiency and insure nominal performance.

All the original conveyors were unsatisfactory and were removed and replaced with more satisfactory equipment. The conveying system is relatively complex, having an over and under configuration with variable speed drives and combining regular belt-type conveyors and pneumatic lines ranging between 5 and 42 in. in diameter. According to plant personnel, the conveying system now works adequately.

The average heating value of the refuse-derived fuel, which is shredded into a 4-in. top size, is estimated to be approximately 7500 Btu/lb. The fuel,

Table 14
Rochester, NY, Fact Sheet

Location:	Rochester (Kodak), New York		
Date:	January 1979		
Contact:	Mr. Bruce Wing Engineering Utilities Eastman Kodak Rochester, New York (716) 458-1000	Owner:	Eastman Kodak
Status:	Operational	Operator:	Eastman Kodak
Capacity:	500 TPD (input)		
Products:		% of Weight:	
	RDF	N.A.	
Process Equipment:		Supplier:	
	Shredder (vertical)	Eidal Corporation (35 TPH)	
	Air classifier	Rader	
	Storage silo	Sprout-Waldron, Co.	
	Boiler	N.A.	
	Note: Boiler rate is 77,000 lb of steam/hour.		
Economics:			
	None available		

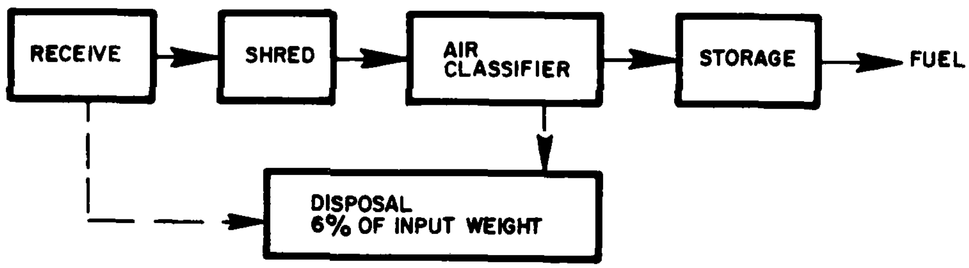


Figure 10. Process description of Rochester, NY, plant.

produced from industrial-type waste, is approximately 50 percent plastic and 50 percent paper, and relatively dry.

The fuel storage bin design is relatively modern, and was designed and manufactured by Sprout-Waldron. Adjacent vertical screws turn in opposite directions to give a lifting movement in the middle of the bin, which provides a good mixing capability and inhibits the tendency of the shredded fuel to bridge. The bin has 14 screws, each being 40 ft high and 18 in. in diameter at the bottom. The bottom of the storage bin, which is 27 ft in diameter, is chisel-shaped.

The plant currently processes approximately 7 1/2 tons of refuse per hour, an amount well below its designed maximum capacity. Each shift includes five laborers and one foreman, as well as maintenance personnel. The plant operates three shifts per day, 7 days a week. Initially, maintenance requirements were rather intensive, with the shredder being the greatest single maintenance problem. Even now, the plant programs 8 hours every week for maintenance activities on the shredder, which include hard-facing and replacing hammers as often as they wear down. Although plant personnel were unable to provide any quantitative data on the frequency of hammer replacement,

they generally felt that hammers should be replaced every 3 or 4 weeks.

Few data on boiler performance are available, but plant personnel have indicated that corrosion has been a major problem, especially in the boiler tubes. Accordingly, they have experimented with coal-firing certain solvents through the boiler system, which has reduced the boiler's corrosion rate. No detailed data were available on the nature of the solvents used, but it is assumed that they are intended to inhibit the rate of corrosion caused by chlorides, the major source of boiler tube wastage. The high rate of chloride corrosion is attributed to the fact that approximately 50 percent of the refuse-derived fuel consists of plastic materials.

Input Characterization

Input to a refuse-derived fuel production facility refers not only to conventional mixed solid waste, but also to special or homogeneous wastes such as pallets, skids, solvents, vehicle lubricants, etc., generated either in a municipality, by an industry, or on a military installation. Determining the amount of solid waste available is the first step, and a very critical step, in planning a facility. It became readily apparent from discussions with plant personnel that little effort had been made during the planning stages of these facilities to adequately characterize the type and amount of solid waste available under normal operating conditions. Such a lack of knowledge can have deleterious effects, including underdesign of conveyors, greater than expected wear on equipment and component parts, overestimation of actual RDF production, and often a lack of economic effectiveness. For example, it is common knowledge that the Ames, IA, facility was planned on the basis that 250 tons per day or more of solid waste would be available to it. However, in reality, this plant rarely receives more than 150 tons per day of solid waste,[50] or only 60 percent of the solid waste required to make its operation break even economically. Such a lack of realism with respect to solid waste availability has been identified as a major pitfall in the planning of such facilities.[51] Similarly, not knowing the quality of the material to be received can lead to the operations and maintenance costs being greater than anticipated.[52] The proper characterization of input to a resource-recovery facility is critical to its proper operation, cost-effectiveness, and determining the characteristics of the product RDF. Accordingly, part of this investigation focused on the characterization of solid waste with respect to the design and operation of resource-recovery facilities. Woodyard has conducted state-of-the-art surveys of solid waste characterization procedures in 1976 and 1978.[53] The following subsections summarize Woodyard's studies, except where otherwise noted.

Solid Waste Survey Planning

Solid waste survey planning involves first assembling information with respect to existing solid waste management practices and then selecting the appropriate solid waste survey method. Specific information requirements may include identification of the waste shed, characterization of existing collection and disposal operations, demographic description of the area serviced by haulers, and previous studies of solid waste characteristics for the study area. In addition, developing a reliable solid waste survey plan involves assessing available study resources, determining study accuracy requirements, and selecting the solid waste parameters of interest.

In planning a resource-recovery facility to produce refuse-derived fuel, it is imperative that the following solid waste parameters be considered. First, attention should be placed on the quantity of solid waste generated within the waste shed. The waste shed may be defined as the military installation including or excluding the surrounding civilian community. Second, it is imperative to be cognizant of the constituency of the solid waste. The constituency can be expressed as mass fractions of recyclable materials such as ferrous materials, aluminum metals, and glass. The constituency of paper, cardboard, and other combustibles must also be known, as well as the mass fraction of bypass wastes not entering the resource-recovery facility. Third, it is important to understand the size and the condition of the waste generated in the waste shed.

[50] Personal communication between Mr. S. Hathaway (CERL) and plant personnel, Solid Waste Processing Facility, Ames, IA (January 1976).

[51] H. Alter, "Pitfalls When Planning Resource Recovery," *Waste Age* (March 1976); H. Gershman and J. Price, "Potholes in the Road to Resource Recovery," *Waste Age* (March 1978); J. Abert, "Resource Recovery: The Economics and the Risks," *Professional Engineer* (November 1975).

[52] S. A. Hathaway, "Potential Systems for Energy Recovery From Solid Waste at Military Installations," *Proceedings of the Second Energy/Environment Conference* (American Defense Preparedness Association, Kansas City, MO, March 1977).

[53] J. Woodyard, *The Prediction of Solid Waste Generation: A Review*, Master's Degree Thesis (Department of Mechanical Engineering, University of Illinois, Urbana, IL, 1976); J. Woodyard, *Municipal Solid Waste Survey Protocol* (SCS Engineers, Long Beach, CA, April 1978).

The size distribution of the waste strongly affects handling and feeding requirements in the processing plant. The general condition of the waste directly affects important plant design parameters and the quality of refuse-derived fuel produced.

Woodyard found that very few resource-recovery facilities considered these factors when conducting a survey, and this was confirmed by the CERL investigation. In nearly all cases, resource-recovery facilities were planned using either waste generation data derived from sanitary haulers within the waste shed or sanitary landfill operating information. In some instances, population data for the area around the resource-recovery facility were employed with EPA solid waste emission factors to derive the number of tons of waste per day were generated in the region. Subsequently, when determining the characteristics of the solid waste with respect to resource-recovery plant design, the solid waste was assumed to have national average characteristics in terms of its constituency of recyclable and nonrecyclable components. Table 15 gives solid waste composition data for several major urban regions in the United States.[54] The average analysis of this solid waste indicates that paper is the largest constituent by mass fraction. The paper content of average solid waste is 45.82 percent by weight. The solid waste stream component having the second highest mass fraction is food waste at 14.22 percent, followed by glass and ceramics at 9.12 percent and metals at 8.84 percent. For comparison, Table 16 lists the composition of typical solid waste for various military installations for which resource-recovery feasibility studies have been conducted in the past. These data show that paper can comprise up to approximately 72 percent by weight of the military solid waste stream. The content of metals in military solid waste ranges between 2.5 and 23 percent, in contrast to civilian solid waste, in which metal content ranges between 7 and 14 percent. The data in Tables 15 and 16 show that there is considerable variation in solid waste constituencies between locations and between the military and civilian sectors. Hence, there is some danger of error if national average solid waste characteristics either for civilian municipalities or military installations are assumed to be present at any one location. These data not only point out the uniqueness of the military solid waste stream, but also indicate the clear necessity for conducting a solid waste survey that is specific to the location for which a resource-recovery feasibility study is being considered.

[54] W. Niessen, "Properties of Solid Waste Materials," *Handbook of Solid Waste Management* (Van Nostrand Reinhold, 1977).

Table 15
National Muncipal-Residential Solid Waste Composition Data
(% by Weight)

(Adapted from W. Niessen, "Properties of Solid Waste Materials," *Handbook of Solid Waste Management* [Van Nostrand-Reinhold, 1977]. Used with permission.)

Location	Food Waste	Yard Waste	Misc.	Glass Ceramics	Metals	Paper Products	Leather, Plastic, Rubber	Textiles	Wood
DeKalb County, GA	16.10	3.76	5.50	5.17	8.71	52.78	2.39	2.38	3.21
New Orleans, LA	11.46	9.81	7.09	9.50	8.21	44.18	3.48	3.32	2.95
Memphis, TN	19.70	12.13	12.53	9.78	6.63	29.67	3.05	4.79	1.72
Long Island, NY	10.0	5.0	6.0	12.0	10.0	47.0	4.0	3.0	3.0
Berkeley, CA	20.06	5.02	7.10	11.33	8.71	44.61	2.11	1.06	
Philadelphia, PA	5.0	–	16.4	9.1	8.4	54.4	1.7	2.6	2.4
San Diego, CA	0.8	2.11	–	8.3	7.7	46.1	5.0	3.5	7.5
Flint, MI	32.6	13.5	0.3	17.9	14.5	17.5	2.3	0.5	0.9
Weber County, UT	8.5	4.2	5.9	4.6	8.4	61.8	2.5	2.0	2.2
Cincinnati, OH	28.0	6.4	–	7.5	8.7	42.0	3.3	1.4	2.7
Alexandria, VA	7.5	9.5	3.4	7.5	8.2	55.3	3.1	3.7	1.7
Atlanta, GA	13.08	1.40	3.18	9.82	8.72	58.34	3.25	1.78	0.43
Purdue Univ. General Analysis	12.0	12.0	14.5	6.0	8.0	42.0	1.7	0.6	2.4*

*Omits 0.8% oil, paint, and chemicals

Table 16
Military Solid Waste Composition Data
(% by Weight)

Location (Reference)	Food Waste	Yard Waste	Misc.	Glass Ceramics	Metals	Paper Products	Leather, Plastic, Rubber	Textiles	Wood
Naval Training Center, Great Lakes, IL*	2.7	1.0	39.0	3.2	3.9	37.4	2.2	2.7	7.9
Mare Island Naval Shipyard, CA+	22.0	–	2.0	–	13.0	50.0	5.0	–	8.0
Naval Amphibious Base, Little Creek, VA†	32.2	4.0	0.8	·	2.5	55.3	0.1	–	5.2
Quantico Marine Base, VA**	6.0	–	17.7	3.6	3.9	62.1	0.7	1.0	5.0
Puget Sound Naval Shipyard, WA++	2.4	·	--		4.7	63.3	--	--	29.6
Ft. Bragg, NC††	12.1	0.8	6.7	1.9	3.2	55.2	11.0	-	9.1
Mayport Naval Station, FL***	11.0	--	2.0	·	23.0	46.0	10.0		8.0
Philadelphia Naval Shipyard, PA+++	0.8	–	3.0	1.0	.5	56.5	9.7	4.5	17.0
Naval Weapons Support Center Crane, IN†††	1.53	0.5	8.01	0.30	2.50	71.6	7.34	1.22	7.00

*S. A. Hathaway and A. Collishaw, *Feasibility Study for Waste Heat Reclamation at Naval Training Center, Great Lakes, Illinois*, Technical Report E-124 (CERL, March 1978).

+S. A. Hathaway, R. Dealy, A. Collishaw, and A. Paine, *Technical Evaluation Study: Solid Waste as an Energy Resource at Mare Island Naval Shipyard, Valleho, California*, Technical Report E-99 (CERL, March 1977).

†S. A. Hathaway and A. Collishaw, *Solid Waste as a Fuel at Naval Amphibious Base, Little Creek, Norfolk, Virginia*, Technical Report E-109 (CERL, June 1977).

**S. A. Hathaway and J. Woodyard, *Technical Evaluation Study: Solid Waste as an Energy Resource at Quantico Marine Base, Virginia*, Technical Report E-93 (CERL, September 1976).

++S. A. Hathaway and J. Woodyard, *Technical Evaluation Study: Energy Recovery Utilization of Waste at Puget Sound Naval Shipyard, Bremerton, Washington*, Technical Report E-89 (CERL, March 1976).

††S. A. Hathaway and J. Woodyard, *Technical Evaluation Study: Solid Waste as a Fuel at Ft. Bragg, North Carolina*, Technical Report E-95 (CERL, December 1976).

***S. A. Hathaway and H. Rigo, *Technical Evaluation Study: Energy Recovery From Solid Waste Incineration at Naval Station, Mayport, Florida*, Technical Report E-51 (CERL, March 1975).

+++H. Rigo, *Technical Evaluation Study: Energy Recovery From Solid Waste at Philadelphia Naval Shipyard, Pennsylvania*, Technical Report E-48 (CERL, June 1974).

†††S. A. Hathaway, J. Woodyard, and A. Collishaw, *Technical Evaluation Study: Energy Recovery Incineration of Solid Waste at Naval Weapons Support Center, Crane, Indiana*, Technical Report E-97 (CERL, December 1976).

Solid Waste Quantity Surveys

Woodyard found three basic approaches to sample selection for solid waste quantity surveys: (1) weighing of all solid waste hauling vehicles, (2) random selection of vehicles to be weighed with extrapolations to estimate solid waste quantity, and (3) use of available truck numbers or volume data in published density conversion figures. Woodyard found that actual surveys reported in the literature for estimating the solid waste quantity included field weighing all refuse trucks in a waste shed, extrapolating data from total truck volume capacity and average weight or density of sample vehicles, and applying per capita waste generation rates established by the U.S. Environmental Protection Agency or by industry. According to Woodyard's findings, there is no generally agreed upon procedure for conducting a solid waste quantity survey. This is true not only in the civilian sector, but also within the Department of Defense. However, within the military, it is generally agreed upon that the proper

approach to determining solid waste quantities generated is to weigh all solid waste collection vehicles before they enter the landfill or other disposal point on or off the installation.[55]

Solid Waste Composition Surveys

Woodyard discovered several methods for selecting and analyzing solid waste samples. Sample selection in composition analysis refers to the acquisition of a portion or portions of the total solid waste flow for subsequent analysis. Either aggregate or nonaggregate sampling techniques may be used. Aggregate sampling refers to the selection of solid waste samples from a large mass of solid waste. Nonaggregate sampling refers to sample representative of a single solid waste generating source.

The overall objective of aggregate sampling is to characterize solid waste as it would be received at a resource-recovery plant. This approach is generally favored over nonaggregate sampling for representing the real situation. Aggregate sampling is best accomplished by drilling samples from a composite solid waste stream, such as a landfill or an incinerator. The largest aggregate sample is a truck load, although typical aggregate samples are much smaller.

Nonaggregate sampling refers to solid waste samples taken at the source of operation. This approach is most often applied when a stratified sampling design is desired or when information on solid waste from a specific source is required. Nonaggregate sampling is usually more expensive than aggregate sampling because the sample collection is added to the sorting crews' responsibilities.

In reviewing aggregate and nonaggregate sampling procedures, Woodyard identified many different protocols followed at various times in various locations. As many as two dozen aggregate and nonaggregate sampling protocols have been identified. It is not known whether any one procedure yields results superior to those of the others with regard to planning and designing resource-recovery facilities. The chief similarities between aggregate and nonaggregate sampling are in the field sampling of solid waste composition, which can be done either by manual sorting or by visual estimation.

Manual sorting involves physically separating the solid waste sample into a prescribed number of categories. The categories selected are usually based on the material composing each waste item, i.e., metal, glass, paper, and other recyclable material. Some sorting programs use category terms such as cans, bottles, newspapers, etc. The separated material is then weighed and each category is expressed as a percent by weight of the total sample. Woodyard has identified nearly two dozen places where such procedures have been followed with varying degrees of success. In nearly all instances, a different protocol for sample selection has been followed. It has not been established which manual sorting protocol is superior with respect to accuracy and precision of estimating solid waste composition for resource recovery.

According to Woodyard, visual composition estimates are generally considered to be less accurate than manual sorting results. However, they are advantageous in that they are inexpensive and easy to implement. Visual estimation procedures can best be classified according to the number of waste categories being studied. Studies of more than three categories generally require a more refined method of waste characterization, while studies of fewer than three categories can often be performed visually. Hence, there are both sample and refined visual methods.

Simple visual estimation begins with a trained observer who surveys a selected solid waste sample and estimates by volume the percentage of waste falling into each component category. The data are then converted to weight percentages, using appropriate densities as conversion factors. This method was developed by the U.S. Army Corps of Engineers and was later incorporated into the Navy Decision Guide for the recovery and reuse of refuse resources. However, instead of applying numerical methods to the sample composition, the observer simply indicates on the data forms whether or not a particular item is present in noticeable proportions. Sample data are subsequently reduced to determine mass fractions of each category.

Woodyard reports several examples of the refined visual technique. One technique is the grid technique, in which a field survey technician is stationed at a landfill. A selected refuse collection vehicle deposits its entire refuse load in a specific rectangular area. A screen made of wire mesh is placed on the refuse, the number of grids overlying a refuse component type are counted, and the number of each component is

[55] S. A. Hathaway and A. Collishaw, *Handbook for the Analysis of Recovery and Reuse of Refuse Resources Data*, Technical Report E-123 (CERL, February 1978).

recorded. Data are then reduced to determine the mass fraction of each constituent category.

The grid count method was further refined through the use of photographs. The photosort method was first reported by Systems Technology Corporation in 1974 and has since been employed in both municipal and military solid waste characterization. In this procedure, a truck selected for sampling deposits its load as it normally would at the landfill. The sampler then takes a color slide of the unmixed pile of refuse. An area representative of the entire load is selected, and the color slide is projected to scale on a gridded screen. The number of times that a specific waste stream constituent occurs under the cross hairs or nodes of the grid is counted. Summary data tabulations are made using density conversion factors to determine mass fractions of each constituent from representative data taken from the slide.

There is considerable debate regarding the efficiency of the photosorting technique. Hathaway, Porter, and Nevers of the Army Corps of Engineers attempted to apply the photosorting technique to a simulated solid waste consisting of seven different homogeneous constituents whose mass and volume fractions were known beforehand.[56] In these experiments, it was found that the photosort technique did not predict the solid waste characteristics accurately. In contrast, Naval Civil Engineering Laboratory personnel applied the photosort technique to solid waste generated at Vandenburg AFB. Their results seemed to indicate that the photosort technique determined solid waste stream composition with respect to resource-recovery potential quite accurately.[57] Therefore, additional experience and experimentation is necessary to determine whether the photosort technique can be used to reliably predict solid waste composition.

Summary and Critique of Input Characterization Procedures

In reviewing information obtained from consultants, system designers, plant operators, and buyers of salvage materials, Woodyard found conclusive evidence that waste characterization has typically been a low priority item during resource-recovery facility design and planning. Waste characterization efforts have typically been confined to the use of published data on solid waste quantity and composition, often referred to as national averages, or to typical characteristics and limited field characterization involving little or no statistical inference. Predictably, survey results are questionable. Both Woodyard's and CERL's review indicated that many solid waste composition and quantity estimation procedures are available and used in the field. It is not known which method is superior for estimating solid waste composition and quantity with respect to precision and accuracy. It is well within the realm of possibility that if two different waste characterization procedures were applied to a single solid waste sample, there would be two different conclusions regarding its composition. However, the degree to whicn these two estimates would differ can only be speculated.

Woodyard's study recommends the use of field surveys to characterize solid waste for several reasons. First, the accuracy of the resulting estimates can be predetermined statistically. Second, results of such a survey are based on local conditions and are more reliable than published information from other sources in both geographic locations and times. Third, the output of such a survey will not only present quantity and composition estimates, but will also characterize the local solid waste management system and develop valuable contacts for later implementation of resource recovery.

Woodyard makes other recommendations with which findings of this investigation concur. First, there must be further verification of protocol and statistical methods used to formulate sample size and precision tables for analyzing solid waste streams. Second, methods for projecting solid waste generation at the municipal and installation levels should be further evaluated. Finally, more research and development should be performed on both the input/output analysis and visual sorting survey methods. When possible, this research and development should be aimed toward improving the accuracy of these methods, since they are inexpensive and can theoretically result in a highly precise and accurate estimate of the solid waste composition.

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[56] S. A. Hathaway, R. Porter, and B. Nevers, *Photographic Fractionization of a Simulated Refuse*, Special Report (CERL, March 1980).

[57] C. Ward and J. Squier, *Solid Waste Source Separation Test at Vandenburg AFB, California, Phase II: Characterization of Intest Solid Waste Management System*, Civil and Environmental Engineering Development Office Technical Report 78-49 (Air Force Engineering and Services Center, Tyndall AFB, FL, December 1978).

Refuse-Derived Fuel Production Equipment and Unit Operations

General Comments

The analysis of operational facilities for producing refuse-derived fuel revealed several commonalities among all the plants. First, all plants began the refuse-derived fuel production process by shredding delivered solid waste. In most cases, shredding was accomplished by a horizontal-shaft hammermill. Five of the production processes magnetically removed ferrous materials during the second operation, usually by magnetic belt conveyor. The second operation in plants where magnetic separation was not the second process was elutriation. Elutriation, or classification, was accomplished either by screening or air classification. Nearly all facilities which chose magnetic separation of ferrous materials as the second unit operation selected air classification as the third operation, and most plants which selected elutriation as the second operation chose magnetic separation as the third unit operation. In most processes where the first three unit operations were shredding, magnetic separation, and air classification, the fourth task was usually screening. Some facilities chose secondary shredding of the refuse-derived fuel feedstock. Hence, the commonalities in refuse-derived fuel production among the facilities evaluated are shredding, screening, air classifying, and magnetic separation of ferrous materials. Subsequent unit operations include air classification, secondary shredding, and storage. For those processes in which a light fluff RDF is produced, DRDF can be produced by adding a pellitizer to the end of the production line. It is understood that this is not a simple addition, and that the pelletizer may be preceded by a unit operation which will more adequately prepare the fluff RDF for the pelletizing operation.

The observation of the above commonalities illustrates the concept of the generic DRDF production process flow as indicated in Figure 1. From this analysis, it is clear that five direct-unit operations are usable for producing shredding, screening, air classification, magnetic removal of ferrous materials, and pelletizing. Depending on the nature of the feedstock and other factors, a secondary shredding stage may be included before the pelletizer. The analysis of operating facilities indicated that unit operations for separating aluminum and glass from the refuse-derived fuel feedstock are optional. Mandatory auxiliary operations are delivery, handling (which includes conveying), and storage. Storage refers to storage either of the prepared refuse-derived fuel or the surge storage of feedstock somewhere within the production process.

No specific reason was obtained from any of the facilities surveyed regarding why operations were sequenced as they were in the plants. It was generally agreed that shredding incoming solid waste was the obligatory first step and that the second step should be removal of magnetic materials. Both of these steps appear to be an effort to reduce the size of the input material to more manageable proportions and to remove some of the materials which deleteriously affect the performance of downstream equipment such as screens and air classifiers. Again, because of general agreement or perhaps even a precedent in unit operations, most personnel felt that a screening or air classification stage should then be applied to the shredded ferrous-free light fraction. After the third unit of production, there was disagreement among plant personnel regarding the next unit operation. Some prefer screening, others prefer magnetic separation, and others prefer another shredding stage. In all cases, personnel spoke of the sequencing not in terms of the quality of fuel product to be derived, but rather in terms of what in-plant process could be installed to make the refuse-derived fuel feedstock more manageable in in-plant operations and more conducive to optimal processing by downstream equipment. In none of the facilities was there a conscious effort or even a deep concern for the nature of sequencing of unit operations, monitoring equipment performance as a function of equipment sequencing and nature of the feedstock, and in attempting to insall more efficient equipment. The selection of equipment and the matter of equipment sequencing has long been a topic needing additional research, development, test, and evaluation.[58]

This investigation attempted a comprehensive evaluation of unit operations, and the following subsections present each unit operation in terms of its description, its principle of operation, models of its performance and operation, and operating experience. Insofar as possible through literature review and facilities analysis, as much scientific and engineering data as possible regarding the operation and performance of equipment have been included. However, the investigation found that such data are lacking in the solid waste processing industry.

[58] *Study of Preprocessing Equipment for Waste-to-Energy Systems, Summary Material and Research Needs* (Midwest Research Institute, Kansas City, MO, 1977).

Solid Waste Delivery

Most modern resource-recovery plants now use trucks to deliver solid waste to a tipping form located within the solid waste process plant building. Prior to delivery, trucks are weighed on either a manual or automatic platform-type truck scale. The preferred mode of operation for the truck scale is automatic, using a driver-ticketing scheme in which the load weight of the identified truck is automatically determined by the scale itself. Typically, the weigh data are printed out in the control office of the solid waste process plant building. Numerous types of scales and weigh stations have been employed, most with considerable success. However, when CERL personnel visited the Ames, IA, solid waste processing facility, the Toledo-type scale there was not working. Plant personnel indicated that the remote printing scale had experienced difficulties ever since the plant was erected and hoped that it could be either repaired or replaced with a similar unit.

For military applications, the tipping floor type of delivery was preferred to the pit and crane type of receiving system. As much as 650 tons per day of delivered solid waste can be handled by a front-end loader delivering solid waste onto a tipping floor,[59] as in the case of the Recovery 1 facility in New Orleans. Although Recovery 1 currently processes approximately 650 tons of solid waste daily, it will process approximately 1300 tons per day in the future. This indicates that the tipping floor front-end loader system can handle the large masses of solid waste typically generated in larger municipalities and certainly on military installations.

The operator of the tipping floor platform and loader system determines what materials should be removed from the solid waste stream and fed by conveyor to the shredder. Throughout the evaluation, it was apparent that the proper operation of all equipment and of the process as a whole depended on operator talent. In this respect, waste processing has changed little during the past century.[60] Moreover, plant management must make a strong, long-term commitment to continuously monitor and improve waste-processing equipment operation.

General guidelines for the configuration of front-end loaders have been developed.[61] To maintain a safe in-plant environment for plant workers, front-end loaders are usually fired with liquid propane gas. In addition, they are equipped with filled tires to prevent blowout and subsequent vehicle outage. An enclosed air-conditioned cab is often used to protect the operator from noise and odor and is recommended in nearly all solid waste processing operations. In addition, the front-end loader should be equipped with roll bar and be rugged enough to insure the safety of the driver in case of an accident. Such front-end loaders are usually equipped with backup alarms. Bucket capacities range from 1/2 to 3 cu yd, and buckets are customarily equipped with tines.

Current solid waste processing facilities require the operator of the front-end loader to mix the solid wastes as it is input to a feed conveyor and to remove adverse materials which may deleteriously affect the downstream solid waste processing equipment. This has resulted in widespread recommendations that front-end loader operators be trained in at least the fundamental aspects of equipment operation in a solid waste processing plant. This reinforces the operator's regard of his/her job and by incorporating training, provides him/her a means of achieving a higher-level position with the process plant.

The tipping floor can usually store some solid waste for a short time. Storage capacity is required on weekends or in case there is a downstream process equipment outage. Because of the nature of delivered refuse, it should not be stored longer than 3 days. To size the tipping floor, a density of 150 lb/cu yd of solid waste is used to convert the mass data measured during the solid waste survey to volume data. Use of this density conversion factor is recommended only when volumes of waste generated within the waste shed are not directly measured for sizing the facility. It is usually unwise to plan for a solid waste pile depth greater than 8 ft high.

The tipping floor should provide enough area for truck turning and for operating the front-end loaders. Working walls must be included to protect other plant elements from waste spillage. Water supply

[59] *Recovery 1, New Orleans, LA* (National Center for Resource Recovery, 1976).

[60] C. Jones, *Refuse Destructors*. London, England (1894).

[61] S. A. Hathaway, *Design Features of Package Incinerator Systems*, Interim Report E-106/ADA040743 (CERL, May 1977).

outlets and drains should be sized to require only periodic manual cleaning. Drain clogging is a frequent problem in solid waste processing facilities; however, this problem currently appears to be unavoidable. Plant design provides for gravity vents, exhaust fans, and fire protection and emergency exits over the tipping floor perimeter. A fire wall may be installed between the tipping floor and equipment room to protect equipment and personnel. In many facilities, deodorants, detergents, and disinfectants are kept in the delivery area to keep it reasonably clean and safe.

Automated Handling of Delivered Waste

In some facilities, solid waste is delivered to the tipping floor and moved by front-end loader into a feed conveyor to downstream equipment. In other facilities, the waste is dumped directly into a relatively shallow live-bottom receiving bin. Both types of facilities have encountered the problem of conveying raw solid waste, although it appears that newer facilities have fewer problems with mechanical transport. The original conveying equipment found in older plants has usually been replaced by more modern equipment that is better designed to handle the delivered material.

Little information was available regarding the design basis of solid waste receiving conveyors. It is well known that there are several variables in such designs, including function, service requirements, method of loading and discharge, treatment of the material and route, volume to be handled, and material characteristics.[62] The function of a conveyor generally determines the type of equipment required, e.g., if material is to be carried horizontally or whether it will be elevated. The service requirements determine the sturdiness or ruggedness of the equipment to be installed; for example, solid waste receiving conveyors, which will experience heavy and continuous service, require heavy equipment. Generally, the use of better equipment provides more economical maintenance and longer life. The most critical points during the handling of bulk materials are loading and discharge, and these will often influence conveyor selection. When designing such systems, consideration must be given to the relationship of the loading rate to the conveyor's capacity in order to prevent spillage and insure efficient, clean, and economical handling. Treatment of the material such as cooling or drying will also influence conveyor selection. Oscillating conveyors are useful for handling some hot materials, and apron, drag, or flight conveyors are satisfactory for moderately elevated temperatures. The volume to be handled determines the conveyor's size and speed. Capacity formulas, charts, and tables for conveyor selection with respect to volume handled are widely available.[63] Perhaps the most critical factors in conveyor selection are the characteristics of the material to be moved and the behavior expected of them. Free-flowing material can be handled by more types of conveyors than sluggish or sticky materials. The conveyor's design and construction must also provide for materials having abrasive or corrosive properties.

The two most overlooked factors in the design and construction of solid waste delivery conveyors appear to be waste volume and characteristics. There is general agreement in the industry on the conveyor's functional requirements and its service requirements, the method of loading and discharge, and material treatment. However, there appears to be some difficulty with regard to conveyor volumetric handling requirements. In many plants, the conveyors handle intermittently large and small volumes of delivered solid waste, an unavoidable situation in small systems where solid waste deliveries are infrequent and unpredictable. It is the task of the front-end loader operator, even in large systems, to insure that a constant and appropriate volume be delivered to the solid waste receiving conveyor. Designation of this responsibility to the operator is being increasingly practiced in many facilities. Accordingly, volumetric-related problems are not as severe as problems related to material characteristics.

When designing and selecting a conveyor, the three most important material characteristics to consider are material size, flowability, and abrasiveness. A material may be very fine, granular, lumpy, or irregular, and it may be very free-flowing or very sluggish. Sluggish material is defined as material with an angle of repose equal to or greater than 45 degrees. The material may be nonabrasive (e.g., talc) or it may be highly abrasive. Special material characteristics must also be considered, including the material's corrosiveness and its tendency to degrade, give off harmful dust or fumes, become very light and fluffy, interlock or mat and resist digging, pack under pressure, and absorb water.

As indicated earlier, little attention has been given

[62] *General Catalog 900* (Link Belt Co., 1950).

[63] *General Catalog 900* (Link Belt Co., 1950).

to material characteristics. Even in solid waste surveys, planners simply measure or even estimate the quantity of material generated. Thus, it can be deduced with considerable confidence that material handling problems originate in the lack of definition of the material to be handled. This problem can be linked directly to the absence of a widely agreed upon protocol for solid waste surveying which considers all the solid waste material characteristics pertaining to the plant's design and construction. This investigation found only one statement of scientific validity with respect to the special characteristics of as-discarded solid waste, which was the observation by Trezek in 1977 that only about 25 percent of the solid waste mass generated by a typical municipality is friable.[64] Even in its testing manual for solid waste incinerators, the U.S. Environmental Protection Agency does not consider the material characteristics of the solid waste to be handled.[65]

This investigation found that there is considerable information within the chemical process industries for designing conveyors for as-delivered solid waste and even for processed solid waste that will function quite well. A great deal of design and selection type information for handling bulk materials with belt conveyors and other types of conveyors exists is available.[66] Similarly, there is a large quantity of information on planning and budgeting a bulk solids conveyor system,[67] as well as significant information about safety aspects.[68] The application of these criteria has not been readily apparent except in very recently retrofitted solid waste plants. The fact that sound and long-proven procedures for conveyor design and construction have existed for many years indicates that the principal difficulty lies with lack of cognizance of the material to be handled.

Even with these difficulties, many solid waste conveying systems have been successful. Some conveying systems for receiving delivered solid waste appear to be operating highly satisfactorily. For example, the outboard steel roller conveyor designed by Rexnord has operated very satisfactorily in many handling applications.[69] This unit is a heavy-duty design that can be used either in single live-bottom receiving bins or in multiple configurations. In the latter case, the bottom of the solid waste receiving bin can have up to four parallel outboard roller steel conveyor which will elevate the material to downstream process equipment. In the Rexnord design, the receiving pit is very shallow in order to ameliorate the problems associated with large deep piles of solid waste, such as the packing and migration of free water. In Rexnord's application, the conveyors are strategically cleated to limit the amount of solid waste tumbling back from the elevating conveyors. The Rexnord design is among the first to seriously consider the characteristics of the material to be handled. Other reviews on the status of the technology for recovering resources from solid waste suggest that the traditional approach toward designing and selecting conveying systems is not very widespread.[70]

Size Reduction

All facilities reduce the size of the solid waste as the first unit operation. In most processes where the waste is mechanically processed to recover its fuel value, secondary shredding may also be desirable. Primary shredding will reduce approximately 90 percent of the mass to an 8-in. top size to facilitate removal of incombustibles. Secondary shredding facilitates suspension burning.[71] When pelletizing of refuse-derived fuel is planned, a third shredding stage may even be required.

Comprehensive reviews of solid waste shredding

[64] Personal communication between Mr. Steve Hathaway (CERL), and Dr. G. Trezek, Meeting for Preprocessing Equipment and Research Needs on Waste to Energy Systems, U.S. Environmental Protection Agency, New Orleans, LA (January 1977).

[65] *Testing Manual for Solid Waste Incinerators* (U.S. Environmental Protection Agency, [USEPA], 1973).

[66] G. Schultz, "Selection and Application Guidelines for Belt Conveyors for Bulk Materials," *Plant Engineering* (September 4, 1975); G. Schultz, "Some Practical Suggestions for Alternative Ways of Handling Bulk Materials with Belt Conveyors," *Plant Engineering* (April 28, 1977).

[67] G. Schultz, "Planning and Budgeting a Bulk Conveyor System" *Plant Engineering* (September 16, 1976).

[68] R. Kulwiec and G. Schultz, "Conveyor Safety Tips," *Plant Engineering* (May 3, 1979); J. Wirenius and S. Sloan, "Safety Handling Solid Waste," *Pollution Engineering* (April 1976).

[69] H. Lisiecki, *Considerations for Evaluation and Selection of Solid Waste Handling Apron Conveyors* (Rexnord Corporation, 1976).

[70] *Report on Status of Technology in the Recovery of Resources From Solid Wastes, County Sanitary Districts of Los Angeles County, Los Angeles, California* (1976).

[71] M. Smith, "Solid Waste Shredding—A Major Change in Waste Control," *Waste Age* (September/October, 1973).

and shredder selection have been published.[72] In addition, the previous discussion of the Madison, WI, facility provides information about the performance of solid waste shredders. It is generally agreed that the horizontal-shaft hammermill is the optimal configuration of shredder for use in solid waste recovery-resource plants. The key findings of this investigation involve four areas: test and evaluation of existing operating and experimental facilities, scientific and engineering research, shredder selection, and hazard associated with the shredder operation. The following paragraphs provide a brief background of the practical aspects of solid waste processing and highlight findings specific to shredders.

There is still considerable debate about the economics of resource recovery. Gorges and Thomas stated the essence of the debate rather succinctly in 1975:

> Even ignoring the occasional ballyhoo of gold from garbage, the question of the economics of resource recovery (materials and energy) from solid waste is far from being settled. Abert claims that resource recovery is now almost as inexpensive as landfill techniques and asserts that a city could recoup its investment in pilot waste projects in two years. On the other hand, Snyder warns that careful consideration is needed before tallying revenues. Resource recovery is capital intensive.[73]

While solid waste processing for *resource recovery* does have its loftier technical-economic issues, it also has an important practical side. The practical problems and successes encountered with solid waste processing directly affect the feasibility of a military installation implementing such a system. While a technology-based resource-recovery system may appear to be cost-effective, its impact on the installation's management structure must be considered.[74] The following synopsis of an article from the Charleston, SC, News and Courier is an example of what frequently goes wrong. Charleston has a solid waste size reduction plant consisting of three hammermills. The plant opened in June 1974 under support of the U.S. Environmental Protection Agency. The plant is a shred and spread type of landfill operation. The landfill is located adjacent to the county size reduction facility. In September 1977, just 3 years after the plant started up, failure of the plant's main shredder forced the dumping of tons of raw garbage directly onto the land to the rear of the plant rather than through the system designed to crush it into an odorless shredded mass. Close to 75 percent of the raw waste brought to the plant daily was dumped directly into the landfill without being shredded. That amounted to 600 tons of raw garbage. According to the Charleston News and Courier:

> Experts were scrutinizing the plant's 40-ton show piece grinder, the first of its type in the world, to figure out what went wrong with its 500 horsepower motor and how to fix it. The motor died May 28 and won't be back in operation until late this month. Officials can't agree on the cause of the failure.[75]

The outage of the solid waste size-reduction plant had drastic effects on solid waste disposal in the county. The News and Courier continued the report as follows:

> Garbage trucks were sinking deep into the raw refuse, and sparks and heat from exhaust pipes set some of the vehicles in the dump ablaze. Fireman were slopping around in the wet muck dragging waterlogged hoses through acres of smelly rotten garbage. Some got sick when they saw mounds of dead animals piled on the landfill instead of buried as required. Eight other firemen once broke out in a rash after fighting fires in the landfill, according to Fire Chief Wilmot E. Guthke. County officials were buying a 50-acre emergency landfill site off East Ferry Road in case the troubles at the plant couldn't be corrected before the county ran out of room to dump the raw waste it couldn't pulverize. To make matters worse, experts informed the county that the plant's equipment with an original life expectancy of some 15 years has seen 10 years of use in 3 years.[76]

Problems and accidens such as the one reported are not infrequent in the solid waste shredding field.

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[72] *Solid Waste Shredding and Shredder Selection*, Publication SW-140/PB261044 (USEPA, November 1974); *Solid Waste Management Technology Assessment* (General Electric Company, 1975).

[73] H. Gorges and A. Thomas, "Critical Assessment of Waste Conversion Energy," *Proceedings of the Institute of Environmental Sciences*, Chicago, Illinois (1976).

[74] S. A. Hathaway, "Evaluation of Small-Scale Waste-to-Energy Systems," *Proceedings of the Third International Conference on Environmental Problems in the Extractive Industries*, Dayton, Ohio (1977).

[75] "Waste Center Hits Three Year Mark – No Celebration," *Charleston News and Courier* (Sunday, September 4, 1977, Charleston, SC).

[76] "Waste Center Hits Three Year Mark – No Celebration," *Charleston News and Courier* (Sunday, September 4, 1977, Charleston, SC).

The review of solid waste production facilities indicated that there is very little monitoring of shredder performance. What must be known is how a specific shredder of a specific configuration and material or construction behaves when fed solid waste of a known composition and quality. Information on electric power consumption, routine and nonroutine maintenance and repair, and overall unit performance is required. Unfortunately, such information is very difficult to acquire because of the sparse efforts made to monitor such equipment. On the other hand, some information on the test and evaluation of shredders is available from the shredding industry. Such information is highly difficult to obtain because of its proprietary nature. The solid waste processing industry is highly competitive, and equipment developers are reluctant to release information on the design aspects of equipment they are developing.

One exception to this general tendency has been the work conducted by the Allis-Chalmers Corporation in Appleton, WI. Their research was very significant in the solid waste processing field, and was unfortunately terminated recently by a corporate recommitment to other areas. Their research on horizontal-shaft hammermills provided important conclusions on overall operation, power requirements, and particle size.[77] With respect to overall operation, Allis-Chalmers found that the great open area and the great arc of the refuse shredder have definite control over shredder operation and performance. Hence, modulating the discharge grate of a horizontal-shaft hammermill will optimize shredder operation and performance. Allis-Chalmers found that power consumption in terms of kilowatt hours per ton processed decreases as grate bars are removed from the shredder. Removing all rear grade bars reduces power consumption by 22 percent over that of normal operation with all the grades in. However, when grate bars are removed, control over shredder performance, shredder operation, and material particle size is sacrificed.

With respect to energy consumption, Allis-Chalmers found that startup power consumption is reduced as the rotor speed of the shaft is reduced. Their research indicated that shredding system capacity is not affected by operation at 900 rpm. Monitoring of the shredder operation both before and after the speed reduction indicated that there was no significant change in material throughput or in the amount of material which could be shredded. Their findings also indicated that a 1000-rpm shredder can be operated satisfactorily at 900 rpm. resulting in a savings of 1.47 kWh per ton processed. This is equivalent to a 21.6 percent reduction in power consumption. However, it was found that the particle size of material from the shredder increased slightly after a reduction to 900 rpm, but such an increase should have little effect on subsequent process equipment, such as air classification or screening. The results of this research, if applied, may provide significant energy savings in shredding operations.

It is commonly known that the particle size of material from the shredder increases as the grate bars are removed from the shredder's discharge end. Allis-Chalmers confirmed previous findings on the power requirements of shredders.[78] In 1977, the company reported that a shredder's power consumption is directly proportional to the size of the material leaving the shredder. For 90 percent of the material passing a 1-in. sieve, approximately 16 kWh of power per ton of refuse are required. On the other hand, for a particle size of 4 in., approximately 4 kWh per ton are required.

A common operation after the shredder is either air classification or magnetic separation. Both of these unit operations are sensitive to the particle size of material coming from the shredder. Considerable research has been done on the particle size reduction capabilities of various configurations of shredders. In the early 1970s, the U.S. Environmental Protection Agency sponsored a long-term investigation of the size reduction capabilities of solid waste shredders. This investigation, conducted by the University of California at Berkeley, pointed to three key factors in shredder performance: energy consumption, wear, and size distribution.[79] A significant finding was that a procedure can be established to determine the specific energy and grate spacing for a particle size from a shredder other that the characteristic size. The characteristic particle size is the size of the particle corresponding to 63.2 percent of the cumulative mass passing a mesh of a selected size. This is predicated on the observation that the size distribution of shredded solid

[77] C. Liddell, R. Brickner, and W. Heyer, *Refuse Shredding Performance Testing and Evaluation Data* (Allis-Chalmers Corporation, 1978).

[78] D. Murray and R. Brickner, *RDF - The Production Hows and Whys* (Allis-Chalmers Corporation, 1977).

[79] G. Trezek, D. Obeng, and G. Savage, *Size Reduction in Solid Waste Processing-Second Year Progress Report, 1972-1973*, Grant EPA R-801218 (USEPA, 1973).

waste particles follows a Rosin-Rammler statistical distribution as shown in Eq 1.

$$Y(X) = 1 - EXP(-(X/X_0)^n) \qquad \text{[Eq 1]}$$

where:

$Y(X)$ is the cumulative percentage of particles passing a screen size of X.

The exponent n, which is sometimes referred to as the n index, is essentially the slope of the line expressed by Eq 2:

$$\ln(1/(1 - Y)) \text{ vs } X \text{ on log - log coordinates} \qquad \text{[Eq 2]}$$

X_0 is the characteristic particle size.

Physically, Eq 1 indicates that for a particular value of the characteristic size, as the value of n increases, the cumulative percent passing a size X decreases, which can be interpreted as larger size particles or a coarser product.

To illustrate the application of these findings, consider a shredder which must be chosen to grind 6 tons per hour and produce a size-reduced product with 90 percent passing a 1.5-in. mesh. Five steps can be followed to make this determination.

1. First calculate the value of $\ln(1/1 - y)$, where $y = 90\% = 0.90, \ln(1/1 - 0.9) = \ln 10 = 2.3$.

2. Locate the screen size to 1.5 in. and ln to 2.3 on a set of appropriate coordinates (Figure 11).

3. Depending on the anticipated n index (slope of curve), construct the necessary curve through the point (1.5, 2.3). For n = 1.0, the slope is 45°.

4. The characteristic particle size, X_0, is then found by intersecting the curve with the value of $\ln(1/1 - y) = 1.0$. For values of n = 0.9, 1.0, 1.1, X_0 = 0.60, 0.65, 0.72, respectively.

5. Now that X_0 has been determined, X_0 = 0.65 for n = 1.0, the use of Figure 12 will give the specific energy as 18 kWh/ton and the grate spacing as 2.4 in., respectively. For 6 tons per hour, 108 kW or 144 HP will be the net grinding energy required to achieve this size reduction.

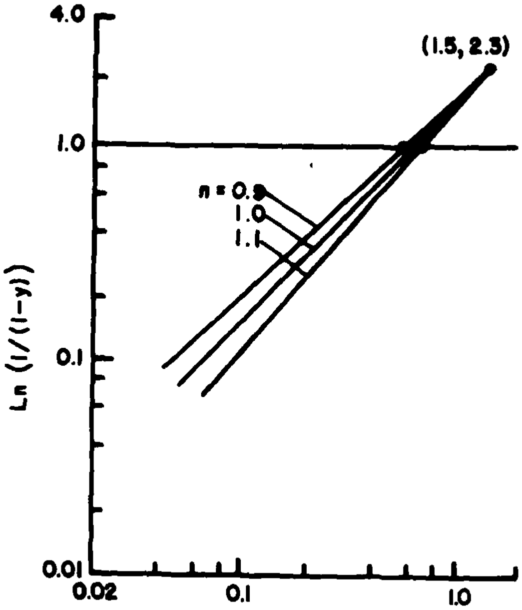

Figure 11. Relation of $\ln[1/(1 - Y)]$ versus screen size for a size distribution with 90 percent passing 1.5 in. (From G. Trezek, D. Obeng, and G. Savage, *Size Reduction in Solid Waste Processing–Second Year Progress Report, 1972-1973,* Grant EPA R-801218 [USEPA, 1973]. Reprinted with permission.)

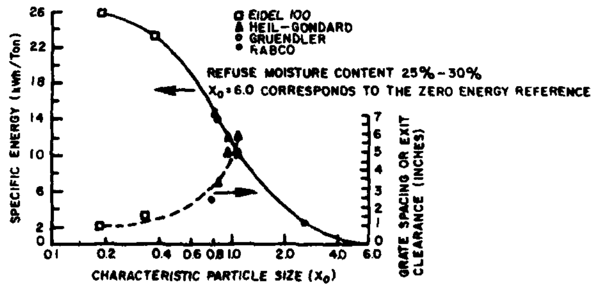

Figure 12. Comparison of the specific energy and exit clearance with characteristic particle size (X_0) for various grinders. (From G. Trezek, D. Obeng, and G. Savage, *Size Reduction in Solid Waste Processing–Second Year Progress Report, 1972-1973,* Grant EPA R-801218 [USEPA, 1973]. Reprinted with permission.)

Other work on the particle size distribution of shredded solid waste has produced similar findings.[80] The existence of a mathematical model for shredder performance is advantageous, because it may be combined with models for downstream equipment such as air classifiers to provide a more precise quantitative determination of the processes occurring during solid waste processing. Moreover, the combination of such models may lead to the derivation of an overall model for a solid waste processing plant which can be used to theoretically study the sequence of unit operations. Currently, however, it is premature to have such expectations. This necessitates determining what can be done now to select and specify a shredder.

Franconeri has provided some excellent shredder selection guidelines.[81] If a shredder is properly designed, the following objectives will be met: the required capacity will be provided, product size will be constant, downtime will be minimal, operating and maintenance costs will be low, and it will be able to handle feed material which contains difficult-to-shred items, such as tires, mattresses, brush, or refrigerators.

According to Franconeri, horizontal-shaft hammermills are preferable to vertical-shaft configurations because they permit positive control over the maximum output particle size. Changes in feed material flowrate or composition will not significantly influence the output particle size. This factor is very desirable when a maximum output particle size is required. The major potential disadvantage of the horizontal-shaft hammermill is that the shredder cannot be free-flowing and as a result, is subject to very high wear rates, overloading, and jamming. In effect, the discharge grate is a restricted opening through which a horizontal shredder will actually try to extrude the difficult-to-shred items. This activity requires shredding power which often exceeds the machine's capability. When this occurs, the shredder can be overloaded and jammed.

Like the horizontal-shaft hammermill, the vertical-shaft configuration is fed from the top, and flow through the machine is controlled by gravity. However, the flow is parallel to the rotor-shaft access. The refuse enters a prebreaking chamber for initial impact and breaking and later enters the grinding chamber which contains the swinging hammers. The refuse remains in the grinding chamber until the particles are small enough to be discharged. A potential advantage associated with the vertical-shaft configuration is that a discharge conveyor is often not required. Moreover, the total required building enclosure height is reduced because the machine discharges shredded material from the side instead of from the bottom. In addition, less electricity is required due to design efficienty. While this advantage is not reflected in shredder cost, it will be reflected in the total system economics. The vertical-shaft hammermill is much less subject to damage, because difficult-to-shred items will pass through the machine and/or will be rejected. Furthermore, the hammers will wear more evenly and at a significantly lower rate, because input material is gradually reduced in size as it passes from input to output, and the force is spread over the entire rotar area.

According to Franconeri, the vertical-shaft hammermill has some potential disadvantages. For example, the required lower thrust bearing has to support the enormous weight of the rotor. This could cause frequent downtime for bearing replacement, and maintenance access to a vertical-shaft hammermill is generally not as good as that of the horizontal-shaft configuration. It is also more difficult to remove the rotor completely or take up its weight to work on the lower bearing. In addition, maintenance access is difficult because of the machine's integral configuration. The upper hammers partially block access to lower hammers, and the available work space is limited. Finally, since a vertical-shaft hammermill does not use a discharge grate, it may not provide positive output particle size control. A vertical-shaft hammermill's average output particle size is a function of only input material composition and feed rate.

Shredders cannot operate 24 hours a day because they require daily maintenance, primarily hammer rebuilding. Therefore, a two-shift operation is most common. This was substantiated during CERL's investigation.

Numerous investigations have been conducted on hammer rebuilding and replacement in solid waste shredders. Kelley has found that most available hard-facing alloys can be placed in one of the following

[80] R. Gawalpanchi, P. Berthouex, and R. Hamm, "Particle Size Distribution of Milled Refuse," *Waste Age* (April 1976); L. Diaz, "Three Key Factors in Refuse Size Reduction," *Resource Recovery and Conservation*, Vol 1, No. 1 (May 1975), pp 111-113.

[81] P. Franconeri, "How to Select a Shredder," *Solid Waste Management* (June 1975, July 1975, September 1975).

groups: build-up materials; low-alloy, iron-base materials; high-alloy, iron-base materials; nonferrous materials; and tungsten-carbide materials. According to Kelley, a low-alloy material consists of less than 20 percent alloy, and a high-alloy material consists of more than 20 percent alloy.[82] Similar work on grinder wear and refuse comminution conducted at the University of California led to several important conclusions about shredder wear rate. This investigation found that when shredder operating speed was decreased from 1200 to 790 rpm, there was a 31 percent reduction in the wear for hard-faced hammers, a 43 percent reduction in wear for nonhard-faced hammers, and 36 percent reduction in wear for grate bars. Furthermore, it was observed that nonhard-faced manganese steel hammers operating at 790 rpm underwent 10 percent less wear than hammers rotating at 1200 rpm that were hard-faced with an impact-resistant alloy.[83] Based on work at the University of California at Berkeley, guidelines have been developed regarding the substitutability of hard-facing coatings for various hammermill base materials (see Table 17).

[82] K. Kelley, "Hard-Facing Shredder Components," *Waste Age* (July 1976), pp 54-59.

[83] G. Savage and G. Trezeck, "On Grinder Wear in Refuse Comminution," *Compost Science* (September-October 1974).

Table 17
Suitability of Hard Facing Coatings for Various Base Materials

(From G. Savage and G. Trezek, "On Grinder Wear in Refuse Comminution," *Compost Science* [September-October 1974]. Reprinted with permission.)

	Facing Alloys					
	Iron-base				Tungsten carbide	
Base material to be hard faced	To 20% alloy	Above 20%	Cobalt base	Nickel base	Inserts	Deposits
Carbon steels:						
0.10 to 0.35% C	Yes	Yes	Yes	Yes	Yes	Yes
0.35 to 1.0% C	Yes (a) (b)	Yes (a) (b)	Yes (a) (b)	Yes (a) (b)	Yes (a) (b)	Yes (a) (b)
Low-alloy structural and constructional steels; 0.30% max C	Yes	Yes	Yes	Yes	Yes	Yes
Gray, malleable and nodular irons	Yes (b) (c)	Yes (b) (c)	Yes (b) (c)	Yes (b) (c)	Yes (b) (c)	Yes (b) (c)
Low-hardenability martensitic stainless (410, 403)	No	Yes (a) (f)	Yes (a) (f)	Yes (a) (f)	Yes (a) (f)	Yes (a) (f)
High-hardenability martensitic stainless (420, 440)	No	Yes (a) (c) (f)	Yes (a) (f)	Yes (a) (f)	Yes (a) (f)	Yes (a) (f)
Type 321 austenitic	No	Yes (c)	Yes (d)	Yes	Yes	Yes
Type 347 austenitic	No	Yes (c)	Yes	Yes	Yes	Yes
All other type 300 austenitic	No	Yes (c)	Yes	Yes	Yes	Yes
Monel	No	Yes (c)	Yes	Yes	Yes	Yes
Nickel	No	Yes (c)	Yes	Yes	Yes	Yes
13% Mn steels	Yes (e)	Yes (e)	Yes (e)	Yes (e)	No	Yes (e)

(a) Preheat. (b) Gas welding preferred. (c) For limited applications only. (d) Use type 347 interlayer. (e) Use nickel-base interlayer. (f) Post-isothermal anneal.

General operating experience with solid waste shredders confirms the observations made in the research described above. It is well known that shredders cannot operate on a three-shift-per-day operation; at least 8 hours a day must be reserved for routine maintenance and repair. Generally, this requires at least 1 man-year of labor and can sometimes be as high as 3 man-years.

The hazard associated with solid waste shredding was a major concern of plant personnel. Factory Mutual Research Corporation in Norwood, MA, annually publishes a report on the assessment of explosion hazards in refuse shredders.[84] The most recent incident of shredder explosion was at the East Bridgewater, MA, solid waste processing facility in which one man was killed. This explosion is currently under investigation. The explosion has tentatively been attributed to an explosion within the primary shredder.[85] Table 18 summarizes Factory Mutual Research Corporation's most recent assessment of explosion hazards in refuse shredders. Several causes have been identified. First, the presence of adverse materials such as paint, gasoline, and solvents has been blamed for many explosions. However, the most common cause has been attributed to the presence of volatile dust from the solid waste, which can be mixed with air in the shredder to form a stoichiometric mixture of air and fuel. Such a mixture can be ignited readily by a spark, and sparks are common inside solid waste shredders.

Designers have produced various solutions to cope with shredder explosion. Some plants place a large wall around the shredder that is comparable to the bomb splinter walls commonly erected during World War II around major heating and power plants. This wall protects plant personnel from the force and shrapnel emitted by a shredder explosion. Many systems have a breakaway panel on the roof of the building above the shredder which accepts the force of the blast and diverts it upward. Other systems use more modern explosion suppression devices such as the Fenwall system. Although they do not have a long history of application to solid waste shredders, explosion suppression systems are becoming more popular. The disadvantage of the Fenwell explosion suppression system is its comparatively high cost in comparison to other alternatives.

Elutriation

The term elutriation essentially refers to air classification of solid wastes. It was found that most facilities in the United States prefer air classification after the primary shredding stage and/or magnetic separation stage. Air classification is essentially a dry method of separating solid waste mixtures either for materials or energy recovery. Air classification of solid waste removes inert heavy materials which detract from the fuel value of the light fraction and recovers "heavy" recyclable materials such as metals and glass.

The three factors that most strongly affect air classification of solid waste are particle size, particle shape, and specific gravity. Numerous configurations of air classifiers have been designed to optimize the interplay between those three major variables. The major configurations of air classifiers now marketed include vertical-chute classifiers, zigzag flow classifiers, and horizontal-chute classifiers.[86] A review of the air classification of solid wastes, including descriptions of the variety of configurations on the market, is available.[87] The vertical-chute classifier is the simplest in design. Essentially, the shredded solid waste is passed into a vertical chute, and a column of air is blown upward from the bottom. The airstream causes the lighter material to fly to the top, while heavier particles drop to the bottom. The percentage separation of heavy and lightweight matter can be controlled by varying the cross-sectional area of the chute and the velocity of the airstream.

The zigzag flow classifer is a multistage zigzag flow column working on the same general principle as the vertical-chute classifier. However, actual separation of the light and heavy fractions occurs at each zigzag in the column. In effect, the sum of the turns of the column gives the effect of multistage separation. This system is superior to the vertical-chute classifier because greater air turbulence is created which can further break up bunched solid waste materials.

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[84] *Assessment of Explosion Hazards in Refuse Shredders* (Factory Mutual Research Corporation, 1978).

[85] "Investigation Started in East Bridgewater Blast Which Killed City Man," *Brockton Enterprise and Brockton Times* (Monday, November 14, 1977, Brockton, MA).

[86] P. Cheremisinoff, "Interclassification of Solid Wastes," *Pollution Engineering* (December 1974); D. Murray, *Air Classifier Performance and Operating Principles* (Allis-Chalmers Corporation, 1978).

[87] *Air Classification of Solid Waste*, Publication SW-30c/PB 214133 (USEPA, 1972).

Table 18

Compilation of Shredder Explosion Reports–Municipal and Bulky Wastes

(From *Assessment of Explosion Hazards in Refuse Shredders* [Factory Mutual Research Corporation, 1976]. Reprinted with permission.)

Location	Shredder Type	Type of Protection	Solid Waste Processed** (000 tons)	Years of Operation	Number of Explosions (fires followed)	Extent of Damage and Injuries	Explosion Per 100,000 tons	Explosion Frequency Per Year	Type of Refuse	Explosive Material
1. Alamoso, Colo.	Vert. Hammermill	Explosion Vents	90	3	0				Mixed	
2. Allentown, Pa.	2 Vert. Hammermills	Explosion Vent	15	0.6	1 - (0)	Minor	6.7	2	Mixed	Flammable Vapor Suspected
3. Altoona, Pa.	Horiz. Hammermill	None	90	20	0 - (0)				Mixed	
4. Ames, Iowa	2 Horiz. Hammermills	Explosion Vent	10	0.3	0				Mixed	
5. Ammonia,* Conn.	Horiz. Hammermill	Water Spray Ex. Vent Panels on Shredder Bldg.	6	0.5	0		0	0	Bulky	
6. Baltimore, Md.	2 Horiz. Hammermills	Ex. Vent Panels and Ducts	30	0.5	1 - (0)	1-major	3.3	2	Mixed	1-Undetermined
7. Beaufort Cty., S.C.	Vert. Hammermill	Explosion Vent	27	1	3 - (0)	3-minor	11	3	Mixed	1-Dynamite 2-Flammable Vapors
8. Boulder, Colo.	2 Vert. 1-Grinder 1-Hammer-mill	1 was vented 1 was not	5.5 5.5	6	0		0	0	Municipal	
9. Chaffe Co., Colo.	Vert. Hammermill	Explosion Vent	16	1	1 - (0)	Minor	6.3	1	Mixed	Flammable Vapor
10. Charleston Co., S.C.	3 Vert. Hammermills	Explosion Vent & Cyclone	300	1	1 - (0)	Negligible	0.5	1	Mixed	Undetermined
11. Chicago, Ill.* 11A (2 Plants)	2 Horiz. Hammermills	Fenwal Suppression System	270	6	0		0	0	Bulky	
12. Columbus, Ohio 3 Locations	3 Horiz. Hammermills	Vents (not explosion)	130	0.7	1 - (0)	1-Moderate	0.8	1.4	Mixed	Flammable Vapor
13. Cowlitz Co., Wash.	Horiz. Hammermill	Explosion Vents	39	0.7 (0)	1-possible	1-Negligible	2.6	1.4	Mixed	Undetermined

*These locations were considered non-representative of MSW shredders and, therefore, were excluded from the analysis.

**Total waste processed during years of shredder operation.

Table 18 (Cont'd)

Location	Shredder Type	Type of Protection	Solid Waste Processed** (000 tons)	Years of Operation	Number of Explosions (fires followed)	Extent of Damage and Injuries	Explosion Per 100,000 tons	Explosion Frequency Per Year	Type of Refuse	Explosive Material
14. DeKalb Co., Ga. (7 Plants)	3 Vert Ham-mill 2 Vert. Grinders	Sprinklers	083	2.8	2 - (0)	2-Negligible	1.3	1	Commer-cial & Municipal	2-Undetermined
15. Elmira, N.Y.	2 Horiz. Hammermills	Fenwal Sup-pression System	127	2	6 - (2)	5-Negligible 3-Moderate	6.3	4	Mixed	2-Flammable Vapors 2-Undetermined
16. Ft. Lauder-dale, Fla.	2 Horiz. Hammermills	Explosion Vent	100	2	2 - (1)	1-Minor 1-Major 1 Injury	2	1.0	Municipal	2-Unknown
17. Galveston, Texas	Vertical Grinder	None Specific-top open	45	1.3	0				Municipal Garbage	
18. Georgetown Co., S.C.	Vertical Hammermill	Explosion Vent & Water Spray	46	2	3 - (3)	3-Minor (fire fight-ing)	6.5	1.5	Mixed-mostly res.	1-Undetermined 1-Propane bottle 1-Boat Gas-Tank
19. Great Falls, Mont.	2 Vert. Hammermill	None	88	2.4	2 - (0)	1-Minor 1-Moderate	2.3	0.8	Mixed	2-Flammable Vapors
20. Guilford, N.C.	1 Vert. Grinder	Water Spray for Dust	75	1.5	4 - (1) (with injury)	4-Minor 1-Injury	5.3	2.7	Mixed	Speculate Chems. + Vapor-but Undet.
21. Harrisburg, Pa.	Horiz. Hammermill	Continuous Water Spray	2.5	2	2 - (0)	2-Minor	80	.67	Mixed	2-Flammable Vapor (Acetylene)
22. Holliston, Mass.	Horiz. Hammermill	None	23	1.8	1	1-Moderate	4.3	0.6	Mixed	Flammable Vapor
23. Houston, Texas	Horiz. Hammermill	None	1,125	10	1 - (0)	1-Moderate	0.1	.1	Mixed	Flammable Vapor
24. Los Gatos, Calif.	Horiz. Hammermill (Sequential)	Water Spray	3.7		0				Mixed	
25. McPharson, Kan.	Vert. Hammermill	"Explosion Chute" on top	13	1	1 - (0)	Minor-but powerful	7.7	1.0	Mixed 50-50 Res-Ind	Explosive
26. Madison, Wisc.	1 Vert. & 1 Horiz. Hammermills	Explosion Vent	360	6	7 - (2)	1-Major 1-Moderate 5-Minor	1.9	1.1	Mixed	2-Flammable Vapors 5-Undetermined

*These locations were considered non-representative of MSW shredders and, therefore, were excluded from the analysis.

**Total waste processed during years of shredder operation.

Table 18 (Cont'd)

Location	Shredder Type	Type of Protection	Solid Waste Processed** (000 tons)	Years of Operation	Number of Explosions (fires followed)	Extent of Damage and Injuries	Explosion Per 100,000 tons	Explosion Frequency Per Year	Type of Refuse	Explosive Material
27. Marlboro, Mass.	Horiz. Hammermill	Manual Water Spray Pressure Relief Openings	47	1.5	0				Mixed	
28. Milford, Conn.	2 Vert. Grinders	Sprinkler Sys. for Dust Control	101	3	13 - (0)	9-Negligible 3-Minor 1-Major	13	4.3	Mixed	12-Undetermined 1-Flammable Vapors
29. New Castle, Del.	4 Horiz. Hammermills	Explosion Vent Panel & Duct Installed 11/75 Vent area–36 ft^2 Input Hopper area–18 ft^2	500	3	14 - (1)	Prior to 11/75 1-Major 2-Moderate 8-Minor, 1 Inj. After Vent 11/75 3-Negligible (successfully protected)	2.8	4.7	Mixed	1-Gunpowder 1-Commercial Flammable Vapor 12-Undetermined
30. Ash Brook, N.J.	Horiz. Hammermill	Explosion Vent. Sprinkle Sys. over unit Water Hose nearby	100	6	1 - (1)	1-Minor	0.3	.25	Mixed	Flammable Vapor
31. Odessa, Texas	Horiz. Hammermill	Explosion Chute	46	2	4 - (1)	3-Moderate 1-Negligible	6.7	2.0	Mixed	2-Paint Thinner 1-Pressurized Cans Ether 1-Undetermined
32. Outagamie Cty., (Appleton) Wisc.	2 Horiz. Hammermills	Water Spray Rubber Curtain	44	1.5	2 - (0)	2-Negligible	4.5	1.3	Residential	2-Undetermined
33. Pompano Beach, Fla.	Vert. Hammermill	None	225	3	1 - (0)	Minor	0.4	0.3	Mixed	1-Flammable Vapor
34. Providence, R.I.	Horiz. Hammermill	None	75	1	0				Mixed	

*These locations were considered non-representative of MSW shredders and, therefore, were excluded from the analysis.

**Total waste processed during years of shredder operation.

Table 18 (Cont'd)

Location	Shredder Type	Type of Protection	Solid Waste Processed** (000 tons)	Years of Operation	Number of Explosions (fires followed)	Extent of Damage and Injuries	Explosion Per 100,000 tons	Explosion Frequency Per Year	Type of Refuse	Explosive Material
35. Pueblo, Colo.	2 Vert. Hammermills	Explosion	36	0.5	2 - (0)	2-Negligible	5.6	4	Mixed	2-Undetermined
36-39. Sacremento Area-4 Locations	4 Horiz. Hammermills	Explosion Vent (Open Design) Continuous Internal Water Spray	1,650	11	1 - (0)	1-Minor (no damage, 4 hrs downtime)	3@0 1@0.2	0.1	Municipal	Dynamite
40. Sacramento Processing Plant	1 Horiz. Hammermill	Ventilation to Pit, explosion doors provided	420	12	Unknown 2 W/TNT	2+numerous (Negligible)	.5	0.2	Municipal	2-TNT
41. St. Louis, Mo.	Horiz. Hammermill	None	59.2	3	1 - (0)	Minor	1.9	0.33	Municipal	Undetermined
42. St. Louis, Mo.	Horiz. Hammermill	None			2 - (0)	1-Moderate 1-Minor	No Frequency Obtained		Bulky	1-Artillery Shell 1-Flammable Vapors
43. San Francisco SWETS	Horiz. Hammermill	Exp. Vent (Open Design) Continuous Water Spray	600	3	1 - (0)	1-Minor	0.2	0.3	Municipal	10 Sticks Dynamite
44. Syracuse, N.Y.	Vert. Grinder	None	150	2	4 - (2)	4-Minor	2.7	2	Mixed	4-Flammable Vapors
45. Tacoma,* Wash.	Horiz. Hammermill (Williams)	Water	60	4	2 - (0)	2-Minor	3.3	0.5	Bulky	2-Flammable Vapor
46. Vancouver, Wash.	Vert. Grinder	Continuous Water Spray	100	2	2 - (0)	2-Minor	2	1	Mixed	1-Fertilizer (commercial explosive) 1-Undetermined
47. Williamsburg Co., S.C.	Vert. Hammermill	Explosion Vent	25	2	3 - (0)	3-Minor	12	1.5	Mixed	1-Dynamite 1-Flammable Vapors 1-Undetermined
48. Willoughby, Ohio	2 Vert. Grinders	Continuous Water Spray	31	2	0				Mixed	

*These locations were considered non-representative of MSW shredders and, therefore, were excluded from the analysis.

**Total waste processed during years of shredder operation.

The third configuration is the horizontal chute. This type has occasionally been used experimentally to classify raw refuse into three light fractions: light, intermediate, and heavy. In typical operations, shredded solid waste is passed into a horizontal airstream which deflects the components as they fall. Adjustable plates allow solids separation at almost any point. The refuse-derived fuel fraction, i.e., the light fraction, is separated out from the system by the air. Heavy materials fall to the bottom, and intermediate matter is moderately deflected by the airstream.

Air classification of solid waste has numerous advantages, including low maintenance, few moving parts, comparatively low space requirements, low product contamination, and suitability to continuous flow operation. Moreover, designs are simple and automated and usually require no manpower. Air classification systems can be designed for material generated from a wide variety of large-capacity shredders, millers, and grinding machines. They generally have low electrical power requirements, and most systems can handle wet, dry, burned, or irregularly shaped matter.

The efficiency and design selection of an air classifier are most directly affected by the nature of the material to be fed into it. The specific properties to be considered are bulk density, particle density, particle shape, and particle size. Factors specific to the air classifier include airstream speed and air column loading. Airstream speed determines the point of separation in both the horizontal and vertical systems. Column loading determines the system's capacity and separation efficiency and directly affects the airstream speed.

Additional equipment required for an air classification system includes a pneumatic conveying system for transporting the fuel fraction to storage, a rugged fan, a discharge tray or hopper for the heavy fraction, an outfeed conveyor, and a motor control center with load and flow indicators. In addition, normal designs have provisions for adding more chutes or stages.

In designing an air classification system, the major factors with respect to material properties are bulk density, particle density, particle shape, and particle size. Particle density affects the material's bulk density and the air-column loading of the air classifier. The bulk density of the material affects the air-column loading and the airstream velocity. It is important to note that the solid waste's moisture content can substantially affect the performance of the air classifier, particularly if the moisture content varies on an hourly or daily basis. Particle shape can be an important factor in determining the air velocity required for effective separation. Particle size is extremely important in designing and selecting air classifiers. Size greatly affects the material's bulk density, the air-column loading, and the airstream velocity.

A variety of air classifiers is used in the solid waste processing industry. One of the first air classifiers ever used was for a demonstration in St. Louis sponsored by the U.S. Environmental Protection Agency. Fluff refuse-derived fuel was produced by primary shredding and air classification. The air classifier, supplied by Rader Pneumatics, operated successfully for several years. Rader found that depending on whether it rained, the density of average shredded solid waste at a top size of 1 1/2 in. varied between 7 and 11 lb/cu ft.[88] Nevertheless, the air classifier system could be modulated to accommodate whatever density feedstock it received. This unit was fed with solid waste through a vibrating feeder and a rotary air lock. The material was pneumatically conveyed directly from the air classifier to the utility boiler nearby. Problems encountered with the operation were due principally to the accelerated wear on the pneumatic transportation system. Personnel solved this problem by strategically placing ceramic baffles at high-wear areas in the lines.

One configuration that has enjoyed increasing popularity is the dual-vortex air classifier developed by Allis-Chalmers Corporation in Appleton, WI, which is constructed so that there are several zones of high turbulence within the columns. Material is fed through a rotary air lock and slides down a preliminary feed chute into the air column. It is theorized that waste breaks apart somewhat when traveling down the feed chute.[89] It is not known whether the dual-vortex air classifier will be superior to other configurations. A unit of this type rated at 70 tons per hour capacity is being installed in Lane County, OR, and Allis-Chalmers hopes that this unit will confirm successful pilot plant data.

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[88]Personal communication between Mr. S. Hathaway (CERL) and Mr. John Kelleyman (Raider Pneumatics, Portland, OR) at Ames, IA (January 26, 1979).

[89]D. Murray, *Air Classifier Performance and Operating Principles* (Allis-Chalmers Corporation, 1978).

Air classifiers currently used in the solid waste processing industry have been increasingly successful in demonstrating their capability to operate within generally liberal boundary conditions for the separation of light and heavy fraction. Of interest in this investigation is research which can lead to modeling solid waste processing systems.

In 1976 and 1977, Sweeney conducted theoretical investigations into the operation of vertical air classifiers,[90] with the objective of determining the feasibility of separating municipal solid wastes into more than two fractions by passing the material through a vertical air classifier. Sweeney demonstrated the feasibility by suspending specimens of varying densities, sizes, and shapes in a vertical air classifier and recording the terminal velocities of the materials. Since most shredded solid waste approximates flat plates of varying sizes and shapes, flat plates of six different materials were evaluated to determine terminal velocity. The materials were in aspect ratios (which is the length over the width) from one to four, and in four different sizes, ranging from .06 to 1 sq in. The materials studied included steel, aluminum, balsa wood, cardboard, paper, cloth, and glass. The theoretical developments and experimental results derived through analysis of variance by statistical testing indicated that municipal solid waste does exhibit a difference in terminal velocity, mostly as a function of density and only slightly as a function of the size and shape of parameters tested. Sweeney therefore concluded that municipal solid waste may be separated into several fractions, provided the proper air classification equipment is used.

Two of Sweeney's findings are notable. His theoretical analysis, statistical analysis, and experimental results indicated that material density is the most important factor governing the performance of solids in air classifiers. He noted that size and shape contribute very little to changes in overall terminal velocity. His experiments also showed that if all solid waste can enter the air classifier in small, flat, plate-like shapes, multiple separation is possible. Separating materials of significantly different densities with an air classifier should be clean, but separating materials of nearly equal densities will be difficult or nearly impossible.

[90]*An Investigation of the Effects of Density, Size, and Shape Upon the Air Classification of Municipal Type Solid Waste*, Technical Report 77-25 (Civil and Environmental Development Office, Air Force Systems Command, Tyndall AFB, FL, June 1977).

Shortly after the appearance of Sweeney's work, Senden and Tels reported their experimental work in vertical air classifiers conducted at Eindhoven University in the Netherlands.[91] Senden and Tels presented a theoretical concept for describing the separation process in a vertical gravitational air classifier. They found that particle movement within the classification zone can be described by two types of transport: a convective transport, which represents the average movement of particles and is characterized by the mean absolute particle velocity, and a mixing transport, which comprises all transport caused by deviations from the average particle displacement. This work assumed that particle inertia is negligible and that the transport parameters are constant along the height of the air classification zone. Rate equations are derived for the removal of particles from the classifications zone. At the heavy fraction exit, the removal rate is assumed to be linearly proportional to the fall velocity of the particle and the relative particle concentration at the heavy fraction exit. At the light fuel fraction exit, the removal rate is assumed to be linearly proportional to the superficial air velocity and the relative particle concentration at the light fraction exit. This research uses the mean residence time of the particles as indirect measure of the throughput capacity of the air classifier. Subsequently, a relationship between the mean residence time and the separation efficiency is calculated. Senden and Tels concluded that suppression of particle mixing and accelerated removal of the particles from the classification zone yields the highest separation efficiency at comparable particle residence time.

The central contribution of the work by Senden and Tels is establishing that a single differential equation, in conjunction with the appropriate initial and boundary conditions, can mathematically describe the problem of particle separation in vertical air classifiers. This is shown as Eq 3.

$$\frac{\partial p(z,t)}{\partial t} = -\mu \frac{\partial p(z,t)}{\partial z} + E \cdot \frac{\partial^2 p(z,t)}{\partial z^2} \qquad \text{[Eq 3]}$$

where:
z = vertical coordinate
E = mixed coefficient
μ = convective velocity
t = time
$p(z,t)$ = probability density of a particle to be in a position z at time t.

[91]M. Senden and M. Tels, "Mathematic Model of Vertical Air Classifiers," *Resource Recovery and Conservation*, Vol 3, No. 2 (May 1978), pp 129-150.

The separation curve and the mean particle residence time can be calculated with relative ease by appropriate manipulations of these expressions.

This investigation found that at the current state of the art, the mathematical development of models for air classifiers is much more advanced for vertical configurations than for others. Both models of air classifiers reviewed in this investigation emphasize the role of particle density in effective separation of light and heavy fractions. When these expressions are coupled with the results of shredder research, it may be possible to evolve a quantitative expression for sequencing shredding and air classification of solid wastes. At the present time, such a model would be relatively crude. Research on shredding has paid little attention to the density of the shredded output material. Rather, it has emphasized the particle size and size distribution of the shredded waste. On the other hand, research in air classification has emphasized the role of material density. Air classification research to date has downplayed the role of the two factors that shredding research has emphasized: particle size and particle shape.

The discussion on air classification of solid waste is not complete without a brief summary of current ideas for air classifying before primary shredding.[92] Tests in a pilot-scale solid waste processing plant owned by Aenco in New Castle, DE, have indicated that air classifying delivered solid waste prior to shredding may have possible benefits, particularly in the area of safety, because this sequence minimizes explosion probability and severity in downstream shredders. Moreover, these experiments concluded that maintenance and process operating costs will be reduced if the solid wastes are preclassified. Whether this concept will apply with equally good results on an operational scale is unknown at this time.

Screening

Screening has been increasingly used in solid waste processing plants. The screens used range from the disc type to the larger rotating trommel screens. So far, operating experience with such systems has been rather scarce, but it is increasing. Accordingly, very few operational data are currently available.

Disc screens are currently being studied in the Ames, IA, Solid Waste Processing Plant. Currently, this plant is being retrofitted with disc screens which will hopefully improve the operation of downstream shredding operations. Theoretically, the screen will remove incombustible, basically inert, and largely abrasive materials and therefore reduce the amount of wear on downstream shredders. An additional benefit of screening processed feedstock will be improvement of air classifier performance. Removing heavy materials with a low-energy type screen should significantly reduce the amount of energy needed by the air-classifying unit to effectively separate heavy materials from the light, refuse-derived fuel feedstock. To date, few data have been published regarding the potential for using disc screens in this manner. Rader Pneumatics, manufacturer of the disc screens being installed in the Ames plant, is confident that their installation goals will be achieved.[93]

Woodruff and Bailes have studied the application of trommel screens to solid waste processing.[94] They have correctly observed that the first step in processing solid waste for resource recovery has usually been shredding. Recently, the authors have reported on research and developmental work conducted during the past 2 years at Recovery 1 in New Orleans. There were two reasons for proposing the use of a trommel for preprocessing solid waste. First, by removing the portion of raw mixed solid waste already within the specified shredder output particle size range and then bypassing the shredder, the throughput and, hence, the shredder's operating costs could be reduced. Second, by removing materials such as glass and cans prior to shredding, the recoverability of the materials would be enhanced. A major assumption underlying this research and development work has been that shredding reduces the particle size of glass to too fine a size, which makes it very difficult to separate from the refuse-derived fuel feedstock. Moreover, glass is a significant contaminant in refuse-derived fuel. Not only does it increase the overall ash content of the fuel and, hence, lower its heating value, it also creates serious abrasion and maintenance problems in subsequent processing and handling steps. In the research at Recovery 1, it was found that by trommeling as-delivered solid waste, 90 percent of the glass could be removed before shredding. Not only

[92] A. Nollet and E. Sherwin, "Air Classifier First, Then Shred," *Proceedings of 1978 National Waste Processing Conference* (American Society of Mechanical Engineers, 1978).

[93] Personal communication between Mr. S. Hathaway (CERL) and Mr. John Kelleyman (Raider Pneumatics, Portland, OR) at Ames, IA (January 26, 1979).

[94] K. Woodruff and E. Bailes, "Preprocessing of Municipal Solid Waste for Resource Recovery with a Trommel- Update 1977," *Proceedings of the 1978 National Waste Processing Conference* (American Society of Mechanical Engineers, 1978).

would this increase the recovery of glass for the salvage market, but it would also significantly protect the shredding system and other downstream equipment. So far, experience with trommeling as-delivered solid waste has been highly limited. Whether reliable quantitative information taken over a long term will be available is currently unknown.

Experiments like that at Recovery 1 were conducted in 1966 in Great Britain.[95] No serious practical difficulties were caused by the mechanical sorting of as-received refuse by a trommel screen. It was also discovered that small materials which do not need shredding and could, in practice, bypass the shredder, could effectively be separated from the waste stream, thereby reducing wear on the shredder and reducing the nuisance of dust downstream.

Although the results of experimentation with trommel screens applied to as-delivered solid waste is very promising, the solid waste industry is rather set against its implementation. Plant personnel preferred preshredding all entering solid waste. Nevertheless, they were willing to attempt pretrommeling wastes on an experimental basis.

Densification

Very little information is available regarding the use of pelletizers on shredded solid waste. Although the National Center for Resource Recovery has been experimenting with the principle of mechanically extruding shredded solid waste, they have published virtually nothing about the scientific and research engineering aspects of their operation.

The ring-type mechanical extrusion mill has nearly universal application, and within relatively broad boundary conditions, has had the highest degree of success in producing pelleted refuse-derived fuel or DRDF.

The first successful pellet mill which used steel dies and rolls was developed in 1931. This unit consisted of a flat steel die with four steel rollers on its surface. Feedstock was fed to the die face and distributed and forced through the die by rollers. The pellet extrusions were cut off or broken off by multiple knives.

The ring-type pellet mill, which uses dies and rollers in a vertical plane, was developed in 1934. Conditioned feedstock is fed and distributed within the working volume by gravity, mechanical deflectors, and centrifugal force. Pressure caused by rotation of the die and rollers compacts the feedstock into a mat on the face of the die and develops the forces which extrude the material through the die holes, forming it into pellets. Adjustable knives shear the extruded material to the desired pellet length. In most modern pellet mills, the die is driven and the rollers are stationary on their axes, but are free to rotate upon contact with the die and the material being pelleted. Two rollers are usually used. Nearly all currently manufactured pellet mills include a feeder, conditioning chamber, die and roller assembly, speed reduction device, prime mover, and base.

Feeder selection is normally based on providing an even feed to the conditioning chamber, assuring an optimal feedstock-to-additive ratio, and modulating the feedstock flow rate. A screw-type feeder is usually employed and, in many units, is integrated into the construction. The conditioning chamber is a simple flow-through mixer having either fixed or adjustable panels. The conditioning chamber can be used to add binding agents. Units are available without the conditioning chamber if self-lubricating materials are to be processed. Most conventional mixers operate between 90 and 500 rpm.

Conditioned feedstock is continuously extruded in the die and roller area. Because die speeds are usually less than roller speeds, the unit is equipped with speed reduction and power transmission apparatus. This apparatus includes direct-coupled gear trains, V-belts, cog belts, and belt and gear combinations. A variable die speed is often desirable for producing an optimal product from a feedstock of variable characteristics, such as shredded solid waste.

Most prime movers are electric motors equipped with amp meters to indicate loading on the main drive motors. This enables the motor to obtain maximum capacity without overloading or stoppage. Drives range between 100 and 250 HP.

A common base is usually furnished to insure proper alignment of the pellet mill and motor and to facilitate rapid, simple, and efficient equipment installation.

Major factors affecting the performance of the pellet mill are feedstock characteristics, die speed, and die characteristics.

DRDF feedstock produced in the process is a highly

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[95] K. Woodruff and E. Bailes, "Preprocessing of Municipal Solid Waste for Resource Recovery With a Trommel–Update 1977," *Proceedings of the 1978 National Waste Processing Conference* (American Society of Mechanical Engineers, 1978).

mixed feed material of variable moisture content, fibrosity, bulk density, texture, granulation, and particle size.[96]

Feedstock moisture content is measurably reduced by combining the functions of process equipment operating before the pelletizer. Some moisture is also lost within the pelletizer itself where operating temperatures can be far above 100°C. The general role of feedstock moisture content is shown in Figure 13 as a function of consolidating pressure to produce acceptable densified material.[97] This is essentially a conceptual diagram and is used to illustrate only generalities in the production of the densified material. The highly nonlinear relationship shows that a greater consolidating pressure is required for dry materials than for materials with moisture contents ranging between 4 and 9 percent by weight. With feedstock moisture content greater than approximately 12 percent, there is a rapid increase in the consolidating pressure required to produce an acceptable densified material. A moisture content of approximately 20 percent requires nearly infinite consolidating pressures which are well beyond equipment capabilities.

It has been sufficiently established that shredded refuse-derived fuel feedstock passing to the pelletizer is highly fibrous. This characteristic generally favors the pelletizer operation because of its high natural binding tendencies. Generally, the greater the fiber-to-particle ratio, the greater the tendency of the equipment to produce an acceptable densified material.

[96] S. A. Hathaway, "Mechanics of Densified Refuse-Derived Fuel," *Proceedings of the Third International Conference on Environmental Problems of the Extractive Industries*, Dayton, Ohio (1977).

[97] J. Johansen, "Factors Influencing the Design of Roll-Type Briquetting Presses," *Proceedings of the Ninth Briquetting Conference* (1965).

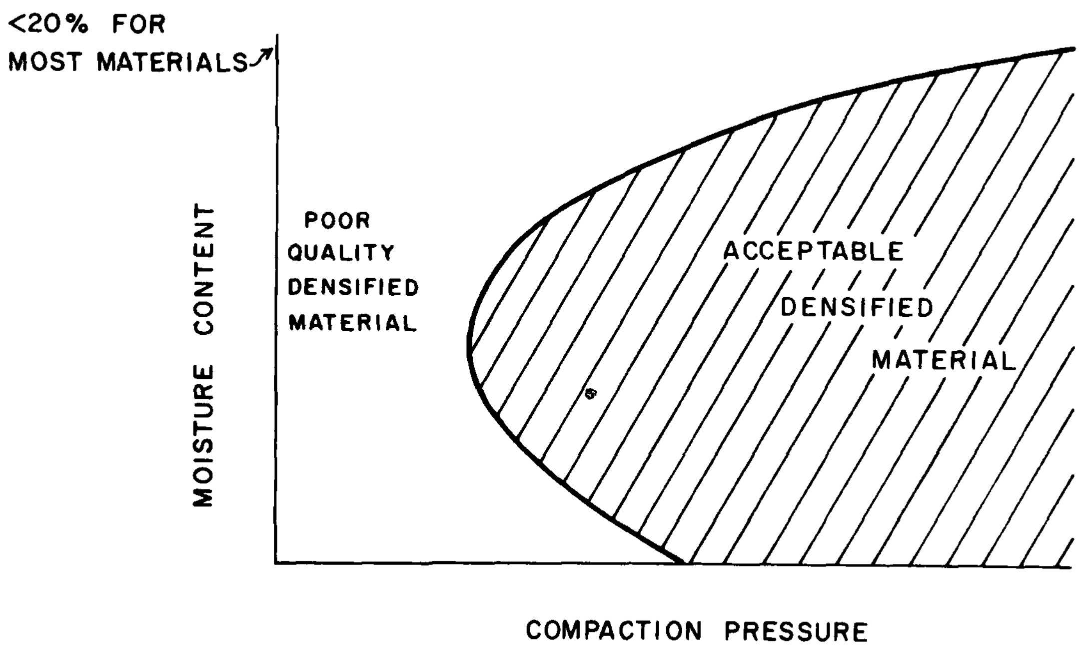

Figure 13. Moisture and pressure conditions for acceptable densified material. (Data derived from J. Johansen, "Factors Influencing the Design of Roll-Type Briquetting Presses," *Proceedings of the Ninth Briquetting Conference* [1965]. Reprinted with permission.)

Fiber is defined as an element having an aspect ratio of 3 or greater. The internal angle of fraction of a solid and, hence, its bulk strength, is directly proportional to the fibrosity of the material and inversely related to the particle fraction.

With all other characteristics being equal, the material's bulk density most directly affects the rate of production. Tertiary shredded solid waste normally has a higher loose bulk density than feedstock which has been shredded only twice. However, in absolute terms, tertiary shredded material can be considered a low-density feedstock.

Die speeds in commercially available pelletizers vary from 130 to 400 rpm. The lower speeds are generally more advantageous for large pellet production and for densifying materials which are not thermally tolerant. Higher speeds are usually more efficient for feedstock havi g a low bulk density. Speeds of 250 ± 10 percent rpm handle the widest range of feedstock, bulk density, and pellet sizes. To capitalize on this variable, many pelletizers are now provided with multispeed capability. Die speed strongly affects compaction time. Figure 14 shows applied pressure expressed as a function of pressing time.[98] For low pressing times, a large applied pressure is required to produce an acceptable pellet. Pressure requirements are reduced to a small degree relative to increases in pressing time and, hence, die speed.

Die characteristics are most often specified in terms of only two parameters: thickness and length. Most DRDF has a pellet thickness of 1/2 to 3/8 in. and a length up to 2 in. The average pellet size is approximately 1 in. long. A specific die is chosen by the mean size of the desired pellet; pellet size is determined largely by the critical dimensions of the coal it will be fired with and the firing method. Generally, large section dies (more than 3 in. thick) do not produce a DRDF that is easy to handle.

[98] J. Johnsen, "The Use of Laboratory Tests in the Design and Operation of Briquetting Presses," *Proceedings of the Eleventh Briquetting Conference* (1969).

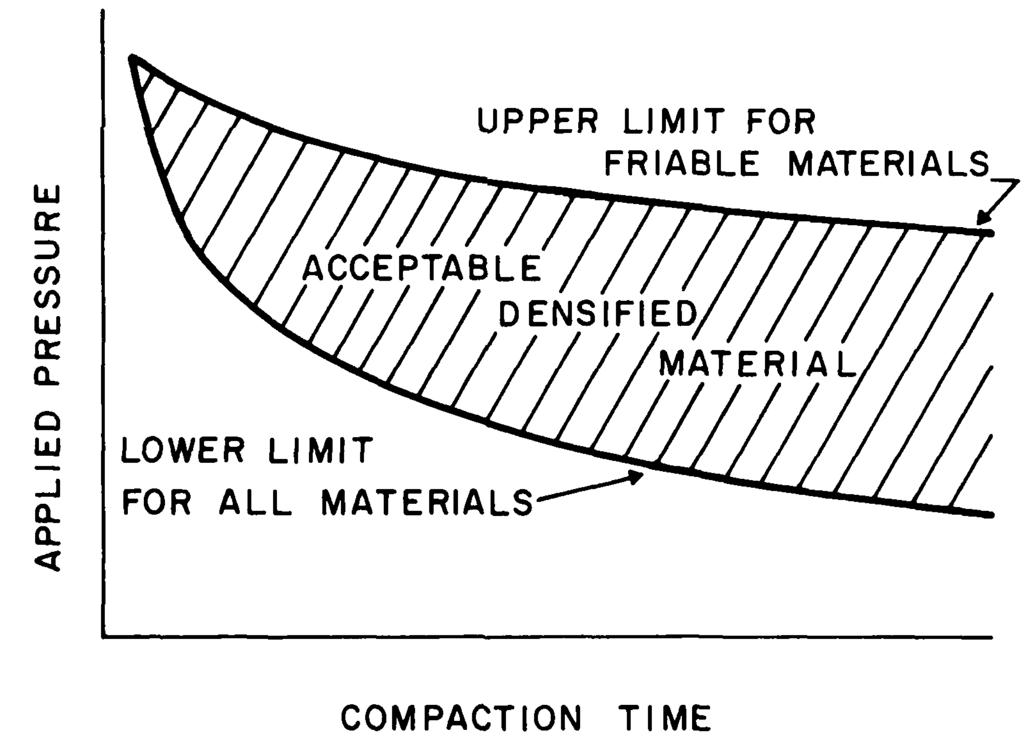

Figure 14. Applied pressure as a function of pressing time for acceptable densified material. (Data derived from J. Johansen, "The Use of Laboratory Tests in the Design and Operation of Briquetting Presses," *Proceedings of the Eleventh Briquetting Conference* [1969]. Reprinted with permission.)

As part of its solid waste program, the Civil Engineering Laboratory at the Naval Construction Battalion Center, Port Hueneme, CA, developed theoretical concepts of densification, particularly the mathematical relationships which govern densification by mechanical extrusion.[99] While the objectives of this work are essentially to develop more economical and environmentally acceptable means to dispose of activity-generated solid waste, the essential theory and relationships of the extrusion processes are mutually applicable on a general level.

The Navy work derived an expression to predict the resisting force of an extrusion die as a function of the size and configuration of the die, the coefficient of friction between the die and the refuse feedstock, and the material strength characteristics of the densified refuse. Amouton's Law and the general form of Hooke's Law were used in this approach. These relationships are stated as Eq 4 and Eqs 5-7, respectively.

$$F = fN \qquad \text{[Eq 4]}$$

where: F = friction force
f = coefficient of fraction
N = normal force.

$$\epsilon_x = (\sigma_x - p(\sigma_v + \sigma_z))/E \qquad \text{[Eq 5]}$$

$$\epsilon_v = (\sigma_v - p(\sigma_z + \sigma_x))/E \qquad \text{[Eq 6]}$$

$$\epsilon_z = (\sigma_z - p(\sigma_x + \sigma_v))/E \qquad \text{[Eq 7]}$$

where: σ = stress
ϵ = strain
E = Young's modulus
p = Poisson's ratio
x,y,z = directions in the Cartesian coordinate system

The Navy model was based on several assumptions. The stress parameters were considered position functions. The assumption of axial symmetry allowed replacement of the y and z stress parameters by a normal stress function. The die was considered to be rigid, allowing transverse strains to be set equal to zero. An integration constant was solved to introduce the compressive stress factor which must be applied to the feedstock at the die inlet to initiate movement through the die. The resulting expression is shown as Eq 8.

$$\sigma_x(x) = \sigma_x(\ell)\, e^{\left[\frac{fP(x-\ell)}{A\left(\frac{1}{p}-1\right)}\right]} \qquad \text{[Eq 8]}$$

where: $\sigma_x(x)$ = axial stress in die
$\sigma_x(\ell)$ = maximum compressive stress
p = die perimeter
ℓ = length of die
A = cross-sectional area of die.

An important conclusion of the Navy work is that the total die resistance may vary as a function of the coefficient of friction and Poisson's ratio, but it is independent of Young's modulus.

Having ascertained the relationships in Eq 7, the Navy conducted experiments to assess the range of the coefficient of friction encountered between densified refuse and steel and to establish Poisson's ratio.

Table 19 presents experimental data obtained by the Navy for the coefficient of friction versus temperature and moisture. Each data point is an average of up to 25 tests run at a particular temperature-moisture combination. The data illustrate an increase in the coefficient of friction with increasing feedstock moisture content and suggest a similar direct relationship to increasing temperature.

Destructive testing of densified refuse slugs showed that Poisson's ratio varies as a function of densification, stress, and moisture. Data collected by the Navy during their tests suggested that density increases directly with stress applied in the densification process in the elastic range of the material.

Conclusions reached by the Navy regarding the densification process indicate that moisture content and temperature of the feedstock are important variables governing the quality of a DRDF product. The work also suggests that the size and nature of feedstock particles directly affect product quality.

Separation of Metals, Glass, and Plastics

Separation of metals, glass, and plastic from the refuse-derived fuel feedstock will result in a relatively superior fuel quality. With the exception of plastics, these materials are inert and increase the fuel's total ash content. Moreover, they increase a boiler's overall

[99] M. Boogay, *Extrusion Parameters for Refuse Densification*, Navy Civil Engineering Laboratory Technical Memorandum M-54-76-25 (Naval Construction Battalion Center, Port Hueneme, California, September 1976).

Table 19
Coefficient of Friction as a Function of Temperature and Moisture

(From M. Boogay, *Extrusion Parameters for Refuse Densification*, Navy Civil Engineering Laboratory Technical Memorandum M-54-76-25 [Naval Construction Battalion Center, Port Hueneme, California, September 1976].)

Moisture Percent of Dry Weight	Temperature °F/°C			
	70/21	150/66	190/88	310/154
7	.12	–	–	–
8	.13	–		.12
9	.19	.19	.17	.14
10	.18	.18	.20	.19
11	.18	.19	–	–
12	.18	.17	.35	–
14	.33			–
15	.33		.16	–
18	.62	–		–
19	.64	–		–
21	.33	–	–	–
23	.61	–	–	–
24	.62	–	.30	–
25	.48	–	–	–
26	.64		–	–
27	.47	.48	–	–
28	.58	–	–	–
31	.60	–	–	–
35	–	.49	–	–
40	–	.49	–	–
45	–	.46	–	–
50	–	.47	–	–

heat loss, increase hauling and disposal costs. It has been well documented that these materials accelerate corrosion and wastage of boiler materials.[100]

Ferrous metals, nonferrous metals, glass, and plastics are often separated from the refuse-derived fuel feedstock for salvage. In some of the facilities investigated, these materials were removed from the feedstock to improve the fuel quality.

[100] Paul Miller and H. Krause, "Factors Influencing the Corrosion of Boiler Steels in Municipal Incinerators," *Corrosion* (January 1971); Paul Miller, H. Krause, and W. Boyd, "The Mechanism in High Temperature Corrosion in Municipal Incinerators," *Corrosion* (July 1972); H. Krause, D. Vaughan, and W. Boyd, "Corrosion and Deposits From Combustion of Solid Waste, Part IV, Combined Firing of Refuse and Coal," *American Society of Mechanical Engineers, Transactions, Journal of Engineering for Power*, Vol 98, No. 3 (July 1976), pp 369-374; H. Krause, D. Vaughan, and P. Miller, "Corrosion and Deposits From Combustion of Solid Waste," *American Society of Mechanical Engineers, Transactions, Journal of Engineering for Power*, Vol 95, No. 1 (January 1973), pp 45-52.

A variety of magnetic separators for removing ferrous materials from processed solid waste are currently available.[101] Generally, magnetic separator design has advanced to a level where high tonnages of shredded wastes (whether from municipal or industrial sources) can be separated continuously, efficiently, and with virtually no operator attention or maintenance. Particularly in recently designed and built resource-recovery facilities, the magnetic separator is often the plant's most trouble-free piece of equipment.

Magnetic separators were originally designed to protect processing equipment from damage by occasional pieces of tramp iron. These magnets were in the form of a magnetic pulley, magnetic drum, or a suspended box-shape magnet. The solid waste resource-recovery industry initially attempted to modify a magnetic drum by adding more magnetic material and positioning the unit more strategically inside the shell. This design was later replaced by a dual-drum design in which a drum was followed by a second drum that was smaller in diameter. However, the efficiency of this design was generally too low to produce a high-volume, marketable steel product, so a different approach was taken. The drum design was discarded early because the amount and arrangement of effective magnetism which can be placed inside a confined cylindrical shape is limited. Moreover, the drum design did not retrieve a clean final product. The newer belt-type ferrous separator is a suspended device which separates ferrous materials by means of mechanical, gravity, and magnetic forces. Magnetic materials are passed through a series of attraction, conveying, agitation, releasing, reattraction, redirection, more conveying, and finally discharging. The discharge is a clean ferrous product ready for sale.

The belt-type magnetic separator now has a reasonably long history of successful operation. Numerous different designs exist.[102] The belt-type magnetic separator is now used in nearly all solid waste resource-recovery plants where removal of ferrous materials from shredded solid waste is required.

The versatility of belt-type magnetic separators was determined by the U.S. Bureau of Mines as long ago as

[101] R. Tobert, "Belt-Type Magnets or Drum Magnets: Which Best Serves Resource Recovery," *Solid Waste Management* (February 1976).

[102] E. Twichell, "One Company's Approach to Ferris Extraction," *Solid Waste Management* (November 1975).

1971.[103] The Bureau set up a pilot plant operation which included an air classifier, a magnetic separator, and a screen for waste shredded to less than 6 in. This pilot facility recovered 92 percent of the metal as a relatively clean iron product contaminated only by adhering coatings or entrapped materials. Not only was the belt-type magnetic separator proven to be technically feasible, but it was also found to be cost-effective when applied to even moderately sized solid waste streams.[104] It is expected that magnetic-type separators will continue to be operated successfully.

Aluminum recovery is not nearly as advanced. The nonmagnetic nature of aluminum, coupled with its rather light density, makes its separation from solid waste technically very difficult. Moreover, there are two diametrically opposed viewpoints pertaining to the separation of aluminum from solid waste. The first contends that aluminum is not a good constituent of refuse-derived fuel and must be removed. The aluminum may be removed in any condition, and at the lowest possible cost. The second viewpoint contends that aluminum is very valuable on the salvage market and therefore must be removed from solid waste in a reasonably good, marketable condition. According to this view, aluminum recovery requires that each successive processing step increase the concentration of aluminum until it can be fed into the separating equipment.

There are three methods of aluminum separation:[105] eddy current separation, density separation, and ferral fluid separation. Not all of these processes have been developed to the stage of commercialization.

Eddy current separators most efficiently recover materials sized from 3.7 to 10 cm. The Ames, IA, solid waste processing plant uses this type of separator and is designed to provide this size range of materials. The Ames eddy current separator has a capacity of approximately 1/2 ton per hour. Combustion Power Company, Raytheon, and Occidental Research Corporation all market eddy current separators. This equipment, which requires a highly aluminum feedstock, uses high-inductive currents to attract the aluminum particles to the sides of a conveyor belt from which they fall into a collecting bin. An eddy current separator was installed in the demonstration Black-Clawson plant in Franklin, OH. When CERL personnel visited that plant in January 1979, the unit was not operating. Plant personnel indicated that the unit required an enormous amount of electrical power (exact data were unavailable) and had never operated up to expectations. CERL personnel visiting the Ames, IA, facility in January 1979 were told that the aluminum recovery system had never worked.

Density separation depends on heavy media and aqueous suspension of fine magnetite, ferro-silicon, or other dense material, and is used for *float-sink mineral* separation. Heavy media separation generally requires a feedstock ranging from 2 1/2 to 5 cm. In front-end separation systems, this size requirement usually necessitates two stages of shredding, followed by screening and water elutriation. A larger shred size causes air entrapment, resulting in excessive losses in both the water elutriator and the heavy-media unit, or in media entrapment in a two-stage, heavy-media operation; this causes excessive aluminum loss in the zinc fraction, where both the aluminum and the entrapped dense media become contaminants in the copper-zinc mixture. Use of heavy-media processing to separate nonmagnetic materials from incinerator residue is not as effective as when the process is used on either front-end or wet-pulping residues, because the metals following incineration are often alloyed. This technology is currently in the developmental stage, and while there has been some experimentation, it is far from commercialization.

Ferrofluid separation is also far from commercialization. This technology is principally used in sweat furnace operations which are widely used in the scrap metal industry. Such operations can separate lead and tin from zinc and will also melt and separate aluminum after recovery of the zinc. Such processing leaves a mixture of copper, brass, and stainless steel, a product that generally can be further processed before use by the copper industry.

The percentage of aluminum recovery differs between heavy-media and heavy-current-separating equip-

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[103] K. C. Dean, C. J. Chindgren, and L. Peterson, *Preliminary Separation of Metals and Nonmetals From Urban Refuse*, Technical Progress Report 34/PB 201900 (U.S. Bureau of Mines, U.S. Department of the Interior, June 1971).

[104] P. M. Sullivan and M. H. Stancyzk, *Economics of Recycling Metals and Minerals From Urban Refuse*, Technical Report Progress 33/PB 200052 (U.S. Bureau of Mines, U.S. Department of the Interior, April 1971).

[105] G. Bourchier and K. Dale, "The Technology and Economics of the Recovery of Aluminum From Municipal Solid Wastes," *Resource Recovery and Conservation*, Vol 3, No. 1 (March 1978), pp 1-18.

ment.[106] All eddy current systems used on the demonstration, pilot, and operational scale are reported to recover between 50 and 60 percent of the total aluminum present in the input refuse. Recoveries of 45 to 90 percent of the feed to the eddy current separator have been reported, with expected recovery typically about 73 percent. The recovery rate of 90 percent is on whole cans and falls to 45 percent on small pieces of aluminum. Overall recoveries have been reported to range from approximately 65 to 90 percent in the various heavy-media stages, with an average of 75.6 percent for material fed to heavy-media equipment. Loss of aluminum at the various unit operations prior to heavy-media separation depends on the characterization of the refuse, the form of aluminum in the input refuse, the size of the shredder output, and the air classification system.

Two basic separation systems for removing glass from processed solid waste are under study: a wet system and a dry system. In both systems, the initial stage separates the organic from the inorganic materials and often the ferrous from the nonferrous components. The processes produce a glass-rich fraction containing such impurities as nonferrous metals, stones, dirt, and various ceramic materials. From the viewpoint of the glass container industry, the problem is to isolate the glass from the other components of this contaminated fraction, so experimentation in color sorting glass has begun. Such a system was installed in the Black-Clawson demonstration plant in Franklin, OH. When CERL personnel visited this plant in January 1979, the glass color sorting system was not operating. However, there was evidence that the glass separation system had enjoyed successful short-term operation. However, plant personnel indicated that the glass separation system worked imperfectly and required a highly trained operator for proper operation.

Two other methods for separating glass from solid waste are being studied.[107] A dense-media technique suspends a metal-based material in a liquid of appropriate and known specific gravity. First, the mixture's density is adjusted so that the glass and other heavy materials sink, and the light materials float and are skimmed off. Then, the glass-rich heavy fraction is passed through a media of different densities so the heavy materials sink, and the glass floats and is skimmed off. In the froth flotation technique, ground glass is placed in a container with an organic fluid that chemically adheres to the glass particles. When air is bubbled through the liquid, glass particles float to the surface and are skimmed off. The liquid can be recycled. As in the case of many aluminum-recovery techniques, methods for recovering metals from solid waste are relatively far from commercialization.

Technologies being developed for separating glass and aluminum from waste materials are aimed principally at treating heavy materials removed from the total solid waste stream. Such removal is usually by air classification, but also can occur by screening. Thus, while such technologies are relatively far from commercialization with respect to their applicability to heavy fractions, they are even further from commercialization with respect to their applicability toward a mixed solid waste stream.

There have been few efforts to develop a technology that will reliably remove plastics. Most plastics found in solid waste have a density comparable to that of cardboard or heavier paper. As such, they tend to be carried with the light refuse-derived fuel fraction, rather than being separated in stages such as air classification or screening. As a result, plastics usually end up in the refuse-derived fuel. The presence of film or rigid plastics in refuse-derived fuel pellets or in DRDF detracts from the internal cohesiveness of the pellets and results in the pellet's tendency to fall apart during transportation and storage.

Summary of DRDF Production

This investigation found that there are few DRDF-producing facilities in the United States. However, there are several producing a refuse-derived fuel that could be pelletized, perhaps without additional preparation. From the previous discussion, it is clear that the nature of raw solid waste and processed solid waste plays a central role in the operation of waste processing systems and unit operations. The solid waste processing plants reviewed have been and still are undergoing suc-

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[106] E. Michaels, K. Woodruff, W. Freyberger, and H. Alter, "Heavy Media Separation of Aluminum From Municipal Solid Waste," *Transactions of the Society of Mining Engineers* (1975); *Fact Sheet, Glass* (National Center for Resource Recovery, November 1973).

[107] *Fact Sheet, Glass* (National Center for Resource Recovery, November 1973).

cessive modifications with varying degrees of success and failure. Procedures for designing unit operations exist, particularly in the chemical process industries; these procedures have probably been followed to some extent in the design of current facilities. If so, the root of the failures and only moderate successes of solid waste processing may be an incognizance of the characteristics of the material for which a plant is designed. In the case of equipment and major unit operations, the principles of operation are generally well known, especially in equipment adapted from other industries. In some cases, the rudiments of mathematical modeling have been surpassed, e.g., for shredders, air classifiers, and pelletizers. Such equipment probably does not perform optimally in solid waste processing plants because there is generally no agreed upon protocol for identifying the vital characteristics of the solid waste which must be known in order to properly design, select, and operate process equipment. The predictable result is a product refuse-derived fuel whose fuel properties, insofar as they are identifiable, vary inconsistently within broad limits, whose marketability to and specifiability within DOD is difficult, and whose performance during continued use in a coal-designed military central heating or power plant may be unpredictable.

4 USE OF DRDF

General Comments

Attempts to use low-grade and waste fuels as substitute fuels in heating and power plants can be traced to the beginning of modern industrial steam generation history.[108] Such fuels have included wood, low-grade coal, refuse, breeze, rice hulls, peanut shells, and a variety of other agricultural-type waste materials. The use of refuse as an energy resource has been considered for as long as 110 years, but the modern origins of using DRDF as well as the beginnings of a subsequent proliferation of technology-based solid waste resource-recovery systems are in the late 1960s and early 1970s.

With respect to the use of DRDF, this investigation found a dichotomy of approaches. The first is more traditional, treating the use of low-grade and waste fuels as a boiler substitution problem.[109] Under this approach, careful consideration is given to the essential design parameters of the candidate combuster. Then an assessment of the fuel quality required for a specified level of combuster performance is made. Such an approach is typical even today when consideration is being given to converting many industrial and military-scale heating and power plants from natural gas or oil to coal.[110]

The second approach is a highly empirical "hit or miss" method. Under this approach, a marketed low-grade or waste fuel is procured and experimentally used in the combuster that is candidate for conversion to this material. Such experiments are typically short term. Rather than first assessing the potential impact of using the waste fuel on the boiler, a wide variety of measurements are taken during actual experimentation. It is then concluded whether or not the fuel can be considered as a substitute in the boiler being tested. This is the approach which has normally been followed when the use of DRDF has been considered. Obviously, there is inherent risk in making a commitment to long-term use of such a fuel based on only short-term tests.

Whether DRDF is to be used at a given military location depends on the cost-effectiveness of implementing it. The economics of using DRDF can be determined once the adjustments and modifications to existing process equipment required for its reliable long-term use have been established. The traditional approach toward fuel substitution considers such adjustments in the planning stages. This approach is characterized as following a scientific method of inves-

[108] F. Goodrich, *The Utilization of Low-Grade and Waste Fuel*, London, England (1924).

[109] W. Schroeder, "Use of Mixtures of Coal and Oil in Boiler Furnaces," *Mechanical Engineering* November 1942); "Converting Two-Stroke Crank Case Scavenging Oil Engines to Producer Gas," *Gas and Oil Power* (January 1943); H. Crain, "Combined Firing of Coal and Natural Gas on Stoker Fire Units," *Transactions of the American Society of Mechanical Engineers*, Vol 65, No. 3 (April 1943), pp 137-141; J. Barkley, L. Burdick, and A. Hersberger, "Collidal Fuel," *Coal Age* (July 1943); D. Gunn, "The Effect of Coal Characteristics on Boiler Performance," *Journal of the Institute of Fuel* (July 1952); O. DeLorenzi, "Influence of Low-Quality Coal on Pulverized Fuel-Fired Units," *Combustion* (November 1952); "Burning of Low-Grade Fuels," *Colliery Engineering* (August 1953); D. Hubert, "Integrating Coal Properties With Boiler Design," *Combustion* (April 1959).

[110] "The Conversion of Solid Fuel in Oil-Fired Appliances to Gas Firing," *Gas Journal* (October 27, 1965); W. F. Coles and J. T. Stewart, *Considerations When Converting Industrial Plants to Coal Firing*, Paper 77-IPC-Fu-1 for meeting 24-26 October 1977 (American Society of Mechanical Engineers).

tigating the use of low-grade and waste fuels. Prior to testing a fuel, a theoretical assessment is made of the entire system's capability to handle that material reliably. During the test, the performance of the material across the entire system is monitored carefully. Differences between the actual material performance and the expected performance then reveal the modifications required for its reliable use. Subsequently, reasonably reliable cost estimates can be derived and a judgment made about the cost effectiveness of using the substitute fuel. The "hit or miss" approach differs substantially from the traditional approach in that a preliminary assessment is lacking, i.e., in scientific terms, there is no hypothesis. Even though the fuel may perform reasonably well over the short term, there is no baseline by which to compare such performance except to the system's original design fuel. An important characteristic of this approach is that it contributes very little to the understanding of low-grade and waste fuels, knowledge which is required for its application in other areas.

This "hit or miss" approach toward the fuel substitution problem has dominated the RDF industry. Accordingly, little scientific information can be offered with respect to the use of DRDF. The historical record is littered with sporadic short-term DRDF product tests conducted by industry and government. A common characteristic of such tests is the attempt to use whatever fuel can be found on the market, rather than defining what is required in the candidate combuster, and subsequently, specifying a usable and producable waste-derived fuel.

DRDF Tests

This investigation found that since 1972, nearly two dozen tests of DRDF in industrial and utility-scale boilers have been conducted [111] (see Table 20); however, data for only five have been documented in reports. One of the most recent tests was conducted in the General Services Administration's Southeast Virginia heating plant in Washington, DC, in March 1979. This test was witnessed by CERL personnel. A report providing the results of this test is due to be published in 1979. Locations of DRDF experiments for which reports exist are Eugene, OR; Piqua, OH; Dayton, OH; and Hagerstown, MD. The following subsections summarize these projects.

Eugene, Oregon

A series of small-scale DRDF test burns was conducted by the Eugene Water and Electric Board between September and October 1974 in Eugene, OR.[112] DRDF pellets of approximately 1/4-in. diameter and 1 in. long were supplied by the now closed Visto Chemical and Fiber DRDF Production facility in Los Gatos, CA. Nearly 21 tons of this material were fired in coal-designed boilers. With respect to fuel handling, this test recommended that a separate weather-protected receiving station be built for the waste-derived fuel, as well as a conveyor feed system to allow solid waste to be added to the existing coal conveyors. There were many dust emission and housekeeping problems during these tests. Moreover, it was recommended that fire hazards and health problems be seriously considered before recommending full implementation of DRDF. This short-term test indicated that on an as-received basis, the heating value of the refuse-derived fuel used was comparable to that of bark. It was generally observed that the DRDF was a "good fuel." The test results indicated that modified firing techniques could be adapted to improve overall operating conditions, including faster, cleaner burning, reduced particulate carryover, and reduced induced-draft fan requirements. Nevertheless, plant personnel anticipated problems with corrosion, erosion, and boiler plugging. This test recommended that DRDF consumption rates not exceed 30 percent of the total fuel required until many of the problem areas have been solved. Moreover, it recommended that a boiler monitoring program and a spare parts inventory be established before any long-term DRDF use is seriously considered. Measurements taken during the test indicated that burning DRDF created a very small size of particulate that existing air pollution control equipment would not capture. It recommended that additional stack cleanup equipment be installed when burning DRDF in order to comply with Government emissions standards. The test indicated that the existing coal-designed ash-removal system has sufficient capacity to handle a 30 percent blend of DRDF and coal. However, it was noted that the rollover ash storage bins were too small to permit night dumping and trucking.

During this experiment, no boiler was operated at design maximum steam-generating capacity for any appreciable amount of time. Therefore, the test pro-

[111] Personal communication between Mr. S. Hathaway (CERL) and Mr. J. Campbell (National Center for Resource Recovery, Washington, DC) (May 5, 1979).

[112] *Solid Waste Fuel Modifications Second Series Burn Tests, Final Report* (Eugene Water and Electric Board, Eugene, OR, December 1974).

Table 20
Summary of DRDF Tests

(Data obtained from personal communication between Mr. S. Hathaway (CERL) and Mr. J. Campbell (National Center for Resource Recovery, Inc., Washington, DC) [May 5, 1979].)

Location	User	Sponsor	Date	Boiler Description	Material Quantity and Description	Producer	Comments
Fort Wayne, IN	Fort Wayne Mun. Power Co.	Fort Wayne	1972	Underfeed-multiple retort	40 T 1 1/2 in. x 1 1/2 in. x 2 in. cubets	National Recycling Corp.	3:1 by vol. (?) 6850-8530 Btu/lb Roy F. Weston
Eugene, OR	Eugene Water & Electric Board	Eugene W&E	10/74	155 M lb/hr traveling chain grate-spreader stoker	21 T 3/8 in. pellets 105 T fluff (from St. Louis)	Vista	Sandwell International five 6 to 7 hour tests
Appleton, WI	Consolidated Paper	Wisconsin Solid Waste Recycling Authority	5/76, 10/76	52 M lb/hr modified for gas; tested with gravity feed, manual ash removal	40 T 3/4 in. pellets	Grumman	Market development test
Waupun, WI	Waupun State Prison	Wisconsin Solid Waste Recycling Authority	6/76	35 M lb/hr spreader stoker-vibragrate	20 T 3/4 in. pellets	Grumman	20-30-40% pellets by heating value Market development test
Oshkosh, WI	U. of Wisconsin	Wisconsin Solid Waste Recycling Authority	11/76	45 M lb/hr spreader stoker-vibragrate gas or coal	20 T 1 1/8 in. pellets 27 PCF density	Vista	1:1 & 1:2 blends Market development test
Green Bay, WI	Fort Howard Paper	Wisconsin Solid Waste Recycling Authority	11/76	275 M lb/hr B&W spreader stoker	40 T 3/4 in. pellets	Grumman	1:3 & 1:2 blends Market development test
Menasha, WI	Menasha Paper Board	Wisconsin Solid Waste Recycling Authority	10/76	165 M lb/hr spreader stoker	20 T 3/4 in. pellets	Grumman	3:2 blend Market development test
Stockertown, PA	Hercules Cement	Unknown	4/75	Cement kiln	Reground 200 T 1 1/8 in. & 5/8 in. pellets	Vista	7 day test–problems in regrind with existing pulverizers
Sunbury, PA	Pennsylvania Power & Light	Unknown	5/75	Suspension fired utility boiler	Reground 80 T 5/8 in. pellets	Heiki Elo	2 day test
Piqua, OH	Piqua Mun. Power Plant	Unknown	6/75	150 M lb/hr C.E. chain grate, gravity overfeed	22 T 3/8 in. pellets	Black Clawson	1:1 vol.; 6400 Btu/lb Franklin pulp product dried and pelletized
Dayton, OH	Wright-Patterson A.F.B.	Air Force	7/75	80 M lb/hr traveling grate–Detroit spreader stoker	40 (?) T 3/8 in. pellets	Black Clawson	34 hr 1:1; 6 hr 1:2 Product as above

Table 20 (Cont'd)

Location	User	Sponsor	Date	Boiler Description	Material Quantity and Description	Producer	Comments
Rantoul, IL	Chanute A.F.B.	Air Force, Army	9-10/75	35 M lb/hr traveling chain grate–gravity overfeed	150 T 1 1/8 in. pellets	Vista	1:1 & 0:1; 4 box cars Material degraded in transit and long storage
Hagerstown, MD	Maryland Correctional Institute (M.C.I.)	EPA	3,5/77	60 M lb/hr Erie City spreader stoker	280 T 1/2 in. pellets	NCRR	58 hr 1:1; 53 hr 1:2; 29 hr 0:1
Hagerstown, MD	M.C.I.	Maryland Environmental Services (M.E.S.)	Fall/78	As above	250 T 1/2 in. & 1 in. pellets	Teledyne	3 test burns over couple months
Spring Grove, PA	P. H. Glatfelter Co.	M.E.S.	Fall/78	Small bark boiler	100 T 1/2 in. & 1 in. pellets and some fluff	Teledyne	Market development test
Maryland–5 Locations	Institutional Boilers	M.E.S.	1977-78-79	Five 10 M lb/hr boilers	<20 T 1/2 in. & 1 in. pellets each test	Teledyne	Market development test
Not revealed	Not revealed	Private	1977	50 M lb/hr underfeed stoker	<25 T 3/8 in. & 5/8 in. pellets	Heiki Elo	Up to 100% pellets Market development test
Not revealed	Not revealed	Private	1978	150 M lb/hr overfeed stoker	<25 T 5/8 in. plant waste pellets	Heiki Elo	Market development test
Vestal, NY	Harper College	Raytheon/State of NY	11/70	100 M lb/hr vibra-grate–mass feed stoker	25 T 1 in. pellets	NCRR	0:1 & 1:1 blend; burn-back; degraded pellets–jams Market development test
Washington, DC	GSA-Virginia Heating Plant	DOE/GSA	3/79	70 M lb/hr underfed multiple retort	125 T 1/2 in. pellets–office wastes	NCRR	30 hr 4:1; 30 hr 2:3; 90 hr 3:2; 6600 Btu/lb
Erie, PA	General Electric	EPA	3-4/79	125 M lb/hr spreader stoker	2000 T 1/2 in. pellets	NCRR 700 T Teledyne 1300 T	
Dayton, OH	Wright-Patterson A.F.B.	Air Force	5/79-10/81	80 M lb/hr spreader stoker–traveling grate	±70000 T 1/2 in. pellets	Teledyne	Contract for $27/ton F.O.B. plant; transport ±30/ton; 1:1 vol. ratio; Promotion of DRDF alternate fuel sources

Criteria Notes: Catalog tests >10 tons pellets from wastes ratios expressed as coal pellets by volume (unless noted)

vides no information about the operability of units running at full capacity using DRDF as a supplementary fuel to coal. Representatives from Babcock and Wilcox Corporation, whose boilers are installed at the plant, recommended changes in some major design parameters if refuse-derived fuel was to be used. These parameters include installing a very tall, generously sized furnace to provide greater retention time for particles burning in suspension, a large-nose arch at the upper portion of the furnace to even out gas flows entering the boiler bank, low final steam temperatures, and a large straight-through boiler bank opened up to reduce gas velocities and minimize erosion. Moreover, they recommended providing room for generous use of soot blowers. The boilers tested had small, short furnace cavities, short-nose arches, high steam super-heat temperatures, and a short, closely spaced boiler bank with multiple passes and relatively minor soot-blower coverage.

Stack sampling data from this experiment indicated that emissions of nitrogen oxides and sulfur oxides appeared to be acceptable and well within the compliance levels for that region of the country. However, particulate emissions exceeded established maximum limitations. Test observers indicated that the quantity of particulates discharge from burning waste-derived fuel was essentially 100 percent greater than the amount produced from burning only wood waste, and many times greater than the amount produced from burning coal. Regional air quality regulatory standards indicate a particulate emission limit of 0.2 grains per standard cubic foot corrected to 12 percent carbon dioxide. All tests exceeded this limitation. The highest amount of particulate measured was 0.49 grains per standard cubic foot, nearly 250 percent greater than the air quality regulatory limit.

Piqua, Ohio

In June 1975, the Piqua Electric Utilities Power Plant in Ohio successfully completed a trial run of a 1:1 volumetric mixture of DRDF and coal.[113] This test was a trial run for a subsequent experiment at Wright-Patterson AFB later that year. In the Piqua experiment, approximately 22 tons of 3/8-in. diameter DRDF pellets made at the Black-Clauson plant in Middleton, OH, were experimentally fired. These pellets had a heating value of 6382 Btu/lb, a moisture content of 16.5 percent, an ash content 9.02 percent, a volatile content of 63.7 percent, a fixed carbon of 10.38 percent, and a sulfur content of 0.22 percent. The pellets had a loose bulk density of 32 lb/cu ft in contrast to the density of the coal which was 55 lb/cu ft.

The boiler tested was a Combustion Engineering type traveling chain grate spreader-stoker rated at 150,000 lb per hour of 454 psig steam at 750°F. The unit was equipped with an economizer and an air preheater, and was installed in 1947. Throughout this test, the maximum steaming rate achieved by using the DRDF-coal mixture was 86,000 lb per hour. This is equivalent to a load factor of 0.57.

According to the test report, the 1:1 volumetric mixture of DRDF and coal was easily carried by the coal-handling system through the overhead bunkers, weighing scales, and into the coal feeder hopper in front of the boiler. Some adjustments in the hopper grate and stoker feed rate were made to compensate for the difference between the bulk density of the mixture and that of coal. Major adjustments made for this test burn included the stoker feed rate, the fuel bed height, and the draft pressure of the boiler. According to the test report, no severe problems were encountered in firing this mixture over the short term.

The received DRDF had a high variability of fuel properties. Moisture content ranged from 12 to 21 percent, ash content from 9 to 17.5 percent, volatile content from 59 to 77 percent, and fixed carbon content from 9.7 to 12.5 percent. Moreover, the heating value ranged from 6100 to 7760 Btu/lb. Sulfur content ranged between 0.14 and 0.33 percent by weight. No air pollutant emissions data are available for this test.

Wright-Patterson AFB

This DRDF test was conducted for 3 days at Wright-Patterson AFB, OH, using DRDF produced at the Black-Clauson Plant in Franklin, OH.[114] Approximately 40 tons of DRDF were fired in a 1:1 mixture with coal and in a 2:1 mixture with coal. Mixes were on a volumetric basis. The combuster tested—an overfeed, traveling-chain-grate, spreader-stoker boiler—was rated at 80,000 lb per hour steam.

The boiler was never operated at designed maximum

[113] *Preliminary Test Report on Handling and Combustion Characteristics of Franklin Pelletized Fuel and Coal Mixes* (Black-Clawson Fiber Claim, June 1975).

[114] J. W. Jackson, *A Bioenvironmental Study of Emissions from Refuse-Derived Fuel*, Report No. 76 M-2/ADA024661 (USAF Environmental Health Laboratory, McClellan AFB, CA, January 1976).

steam-generating capacity. The highest load achieved on the boiler during the test was 0.63. Pellets used compared well to those used in the Piqua test with respect to fuel properties. Air pollution data taken during the test indicated that particulate emissions were the same produced when coal alone was fired. Sulfur dioxide emissions were reduced up to 50 percent when a 2:1 coal/refuse-derived fuel mixture was fired, and emission of total hydrocarbons was reduced up to 97 percent. When a 1:1 mixture was fired, nitrogen oxide emissions were reduced by one-third, but when a 2:1 mixture was fired, nitrogen oxide emissions increased by 100 percent. Moreover, at a 2:1 mixture, lead emissions increased by 3400 percent, chloride emissions by 340 percent, and fluoride emissions by 700 percent. These important environmental consequences must be dealt with when considering use of refuse-derived fuel. Such emission levels can be anticipated at any location where DRDF is fired.

Hagerstown, Maryland

The Systems Technology Corporation conducted numerous short-term tests in which a DRDF and coal mixture was burned in small institutional-scale spreader-stoker-fired boilers at the Maryland Correction Institute in Hagerstown, MD.[115] These tests were conducted under a grant from the U.S. Environmental Protection Agency in 1977 and 1978. Although this test has been rather highly publicized, it is noteworthy that no single test firing lasted longer than 123 hours on the boilers evaluated. DRDF was produced and supplied by the National Center for Resource Recovery in Washington, DC. It was fired in varying mixtures with coal in two spreader-stokers rated at 60,000 and 72,000 lb per hour nominal capacity, respectively. The boilers produced saturated steam for heating and cooling the institution. Data collected during the test are very sparse and do not enhance any firm judgment about the viability of firing DRDF in such boilers. The boilers were operated at a highly variable load. Load rating of the boilers during all tests varied between 5 and 70 percent. The average boiler load during the test was approximately 50 percent. During the experiments, it was noted that overfire airflow had to be increased dramatically to obtain optimal combustion of the fuel blends. In addition, when 100 percent DRDF was fired, the bottom ash-handling system was overtaxed. Fuel feeders attained maximum capacity with 100 percent DRDF at 70 percent boiler steam load. One conclusion from this test is that there would be predictable boiler derating when both high RDF substitution ratios and high steam mass flow rates are accepted simultaneously.

One concern in this test was air pollutant emissions. Measured stack gas opacity during the test ranged between 40 and approximately 95 percent. As in the Wright-Patterson AFB tests, there were few problems with sulfur oxide emissions. Nitrogen oxide emissions data indicated that increasing amounts of refuse-derived fuel in the mixture apparently cause an emission decrease followed by a slight increase. These experiments indicated that the trace metal content of the stack gas particulate would be substantially enriched as the refuse-derived fuel in the mixture is increased. Enrichment rates of 52.6, 33.6, 14.5, and 6 were measured for cadmium, lead, zinc, and chromium, respectively. These rates were measured for a 2:1 refuse-derived fuel to coal mixture. At this level of substitution, an enrichment rate of approximately 10 was observed for copper, 5 for lead, and 2 for chromium in bottom ash collected from the furnace. An enrichment rate of approximately 3 was measured for manganese. These results, along with observations made at Wright-Patterson AFB, indicate that sophisticated and costly particulate air pollution control equipment may be necessary when DRDF and coal are fired.

Systems Technology Corporation is currently conducting similar tests on a somewhat larger boiler in Erie, PA. The report from this test should be available at the end of calendar year 1979.

Combuster Performance

The review of DRDF field tests has indicated that only sparse analytical data are available and that the general testing approach is the "hit or miss" type. There is apparently no scientific method used in any of the DRDF tests reported on and evaluated by this investigation. Accordingly, the state of the art of RDF use is just that—an art, not a science. Although many thousands of dollars have been expended for DRDF experiments, the field has advanced little beyond its development when Hollander and Cunningham conducted their first experiments in 1972.

There are several major reasons for this lack of advancement. First, it is common knowledge that solid waste management in both large and small municipalities (and also on DOD installations) has never represented enough of a business opportunity to support extensive internal or sponsored research by equipment vendors, universities, or research institutions. Second,

[115]*A Field Test Using Coal: DRDF Blends in Spreader Stoker Fired Boiler* (Systems Technology Corporation, 1978).

municipal governments and most industries have had neither the money nor the incentive to fund extensive analysis efforts as part of the design process. Indeed, many of the DRDF tests conducted, and for which no reports have been published, have been market-development tests. Third, the technical complexity of refuse-derived fuel use and the general fuel substitution problems have evidently failed to stimulate investigations by the academic community. Finally, the technical responsibility for solid waste disposal has usually been given to firms and individuals skilled in civil and sanitary engineering, in which high-temperature reactions, mixing, radiation, and other processes are simply not part of the standard curriculum.[116] Moreover, particularly within DOD, there is an apparent absence of a long-term commitment to the research, development, testing, and evaluation required to develop DRDF use to a point where it can be used reliably, cost-effectively, and environmentally compatibly in military central heating and power plants. DOD research programs are typically funded on a 1-year basis, which presents a problem in establishing a year-to-year continuity in programs requiring many years to complete. Attempts at establishing multiyear research, development, testing, and evaluation projects can easily be satisfied by the year-to-year reprioritization of research needs.

Obviously, there is need for a multiyear commitment to the development of DRDF as a reliable supplementary and substitute fuel in military heating and power plants. It must be noted that combustion processes are highly complicated; any analytical description of combustion system behavior requires consideration of three key areas of inquiry. First, the chemical reaction kinetics and equilibrium under nonisothermal, nonhomogeneous, and nonsteady conditions must be investigated. Second, there must be a quantitative understanding of fluid mechanics in nonisothermal, nonhomogeneous reacting mixtures with heat release which can involve laminar, transition and turbulent, plug, recirculation, and swirling flows within geometrically complex inclosures. Finally, there must be a quantitative appreciation of heat transfer by conduction, convection, and radiation between gas volumes, liquids, and solids with high heat-release rates and, in boiler systems, with high heat-removal rates. These factors alone contribute substantially to the high level of complexity encountered in the study of combustion systems. This complexity is often increased by frequent unpredictable shifts in fuel composition, resulting in changes in heat-release rate and combustion characteristics. Compounding these process-related facts of combustion are the practical design and operating problems in materials handling, corrosion, odor, vector control, residue disposal, associated air and water pollution control, and a large number of social, political, and regulatory pressures and constraints.[117] Accordingly, the proper evaluation of combuster performance when DRDF is used, either as a supplement or as a substitute fuel, clearly requires a large team of engineers and scientists with a wide variety of mutually complementary academic and experience backgrounds. Throughout the history of DRDF test and evaluation, such a team has never been assembled. As a result, the proper evaluation of boiler performance when fired with DRDF has suffered.

This investigation found that although there are very few data pertaining to actual field experience with DRDF and its proper performance measurement, the opposite is true of sources providing general performance evaluation guidelines.[118] Nevertheless, this investigation uncovered few studies in which the problem of DRDF substitution was quantitatively worked through, even on a very superficial level.[119] It is probable that similar studies have been made in the solid waste processing and refuse-derived fuel industry, but these efforts have never been formally reported.

Shortcomings in experimental design and conduct with DRDF were well recognized before this investigation was begun. Accordingly, CERL issued a contract

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[116]W. Niessen, *Combustion and Incineration Processes* (Dekker, 1978).

[117]W. Niessen, *Combustion and Incineration Processes* (Dekker, 1978).

[118]*Steam* (Babcock and Wilcox Company, 1978); *Combustion Engineering* (Combustion Engineering Corporation, 1968); W. Niessen, *Combustion and Incineration Processes* (1978); "Experimental Diagnostics in Combustion of Solids," *Progress in Astronautics and Aeronautics,* Vol 63 (1978); R. Goulard, ed., *Combustion Measurements, Modern Techniques and Instrumentation,* Project Squid Workshop on Combustion Measurements in Jet Propulsion Systems (Academic Press, 1976); A. Kanury, *Introduction to Combustion Phenomena* (Gordon and Breach, 1975); *North American Combustion Handbook* (North American Manufacturing Corporation, 1978); E Hoffman, *The Concept of Energy* (Ann Arbor Science, 1977).

[119]S. A. Hathaway and R. Dealy, *Technology Evaluation of Army-Scale Waste-to-Energy Systems,* Technical Report E-110/ADA042578 (CERL, July 1977); H. Hollander, "Parametric Consideration in Utilizing Refuse-Derived Fuels in Existing Boiler Furnaces," *Proceedings of 1976 National Waste Processing Conference* (American Society of Mechanical Engineers, 1976).

for determining the critical combustion system parameters to be monitored in a long-term DRDF experiment. This contract will also recommend an evaluational protocol for monitoring the experiment. Concurrently, the Air Force is evaluating alternative locations for a long-term DRDF-coal experiment. Once this location has been resolved, boiler data will be obtained and carefully analyzed to establish scientific hypotheses for testing DRDF performance. The contracter-derived experimental protocol and monitoring system will be applied to collect data and reject or verify these hypotheses. It is hoped that prudently conceived and carefully conducted experiments with DRDF and coal mixtures in military-scale heating and power plants will have future military benefits, including the establishment of general guidelines for implementing DRDF systems.

DRDF Storage and Handling

The proper handling and storage of processed solid waste and refuse-derived fuel product has long been recognized as a severe difficulty. The economic effectiveness with which DRDF can be used in a military central heating and power plant depends in part on its ability to be handled, stored, and fed in systems designed for coal. Systems in which substantial modifications are required (such as bunker replacement) may not be able to use DRDF economically. A typical military central heating and power plant burning coal has handling and storage operations which include receiving, elevating to a bunker, storage in a bunker, feeding from a bunker, and feeding to the boiler. Usually, bunkers are designed to hold 3 to 5 days' worth of fuel (coal or DRDF). There is usually a separate fuel storage area near the boiler plant. In typical operations, the fuel is delivered to the outside storage area and periodically moved to the boiler plant's active storage area. Accordingly, the outside storability of the material must be considered.

This investigation uncovered relatively sparse data regarding outside storage of DRDF. During the DRDF and coal tests conducted in Washington, DC, by the National Center for Resource Recovery in March 1979, approximately 100 tons of DRDF were stored adjacent to the testing area on a concrete slab. The pile of materials was relatively shallow, averaging approximately 4 1/2 ft in height. It was covered by tarpaulins weighted down by rubber tires. The DRDF was produced several miles away; it was hauled to the storage area and was stored for approximately 1 month. Personnel observed that the DRDF tended to deteriorate during outside storage, even though it was covered. This deterioration was attributed to the flow of free moisture within the pile itself and to the fact that the pellets give off heat. The latter phenomenon is caused by surface crusting of the pile. Another problem with outside storage observed during this test was that a portion of the stored DRDF froze during the winter months. For these reasons, personnel closely involved with the experiment did not recommend outside storage. Because the outside storage capabilities of DRDF are limited, numerous designs for enclosed storage have been drawn up.[120] To date, such storage vessels have achieved moderate success. Of particular interest is the atlas bin. The performance of newer models is apparently superior to that of earlier configurations. However, storage capacities of vessels located externally to a boiler plant are highly limited. It is doubtful that facilities could be erected which could store the 30, 60, or 90 days' worth of fuel required by an average military central heating or power plant.[121] Therefore, it is probable that any use of DRDF within the military in the immediate future will require that it be delivered directly to the active storage area in the plant's bunker as it is required.

There is considerable debate regarding the handleability and storability of DRDF in military-scale coal bunkers. Some test reports indicated little problem, if any, regarding the storability and feedability of DRDF in and from coal bunkers. In some tests, notably the ones conducted in Hagerstown, MD, there was sufficient apprehension about flow problems from the coal bunker that the coal-handling system was bypassed when DRDF experiments were conducted. In the extreme case, one of the earliest DRDF experiments conducted by CERL at Chanute AFB, IL, in September and October 1975, indicated the potential for severe no-flow problems with refuse-derived fuel in in-plant coal-storage vessels.

The current industry approach toward storing and handling DRDF is twofold and resembles the dichotomous approach toward using DRDF in boilers discussed earlier. One approach is the "hit or miss" approach. During tests or experiments, DRDF is fed to existing

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[120] W. Hickman, "Storage and Retrieval of Prepared Refuse," *Proceedings of 1976 National Waste Processing Conference* (American Society of Mechanical Engineers, 1976); C. Fisher, "Live Center Bin," *Proceedings of 1966 National Waste Processing Conference* (American Society of Mechanical Engineers, 1976).

[121] *Report on Status of Technology in the Recovery of Resources From Solid Wastes, County Sanitary Districts of Los Angeles County, Los Angeles, California* (1976).

coal-designed storage equipment. During the experiment, an evaluation is made with respect to the performance of the material in and from the vessel. Typically, such evaluations consist merely of a statement that it either did or did not function well. The other approach is carefully analyzing properties of the DRDF that will be fed into a bunker, carefully evaluating the bunker properties (its geometry, load capacity, materials of construction, etc.), and then deriving a theoretical notion about the material's potential performance. In some cases, notably coal storage bunkers having a semicircular cross-sectional profile, the theoretical deductions from such analysis could lead to a decision not to use the bunker for storing refuse-derived fuel since its potential for gravity mass flow out of the vessel into the coal feeding equipment is very low.

The mathematical theory of the design and performance of gravity mass flow storage bins (such as a coal bunker) was formulated during the 1950s at the University of Utah.[122] The quantitative theory of mass flow bins which now exists in the chemical process industry post-dates the construction times of most military coal bunkers. The designs of the bunkers were usually based on the designers' experience and/or intuition. Accordingly, there are an extremely wide variety of coal capacities, configurations, geometries, and construction materials in military bunkers. They may or may not have been designed specifically to handle either the coal currently fired or the coal that would be fired if the plant were converted to coal. In some cases, coal bunkers designed for one type of coal will not perform well when they receive another coal.

This investigation found that only in one case was the quantitative theory for designing bulk solids storage and flow systems applied to refuse-derived fuel.[123] This study demonstrated the vast difference in flow properties between Illinois bituminous coal and various types of fluff and densified refuse-derived fuel currently produced. While the study did not lead to a definitive design for a gravity mass flow DRDF storage vessel, it did indicate the need for research into the mechanical properties of DRDF and pointed out that there are established methods in the chemical process industries for designing such systems which can be applied to establish reliable DRDF handling and storage systems. The analytical methods and design procedures developed in the 1950s by Jenike can be used both for designing new facilities and for modifying existing vessels.

The potential problems of storing and feeding DRDF in coal-designed bunkers were recognized at the beginning of this investigation. Accordingly, CERL issued a contract for analyzing DRDF samples to determine their essential flow properties and to derive a definitive design for a storage vessel that would hold approximately 100 tons of material. Results of these analyses will be reported in Phase II of this study.

In-place coal bunkers must probably be modified somewhat in order to reliably store and handle DRDF. Such modifications may include a slight change in geometry, a change in construction materials (usually accomplished by putting in liner material), and enlargement of the hopper outlet. The costs for such modifications are currently only speculative because they will be largely site-specific. In the design of any DRDF storage system, provision also must be made to ameliorate fugitive dust emissions typically encountered when DRDF is passed through a coal-handling system. The overall economics of a reliably operating and safely performing DRDF handling, storage, and feeding system cannot be determined at this time. However, some cost will be entailed in revising existing systems to accommodate DRDF. Such costs will typically be only first costs, with the exception of power required to run dust collection equipment. Whatever their magnitude, these costs will enter into the cost-benefit analysis when the economics of using DRDF at a specific location are investigated.

Summary of DRDF Use

This investigation found that experience with using DRDF as a substitute and supplementary fuel is very sparse. Approximately two dozen short-term DRDF tests have been conducted in industry and government over the past 7 years. Of these, reports on only four have been issued, which has greatly limited the ability to define future actions with respect to using DRDF. Generally, all DRDF experiments have selected a product on the market and attempted to experimentally use it over a short term in existing heating or power plants. The investigation found little scientific design in the conception and conduct of such experiments. Accordingly, from a scientific standpoint, very little has been accomplished from such tests. The absence of the scientific approach also pervades those portions of

[122] A. Jenicke, *Storage and Flow of Solids*, Utah Engineering Experiment Station, Bulletin No. 123 (University of Utah, November 1964).

[123] S. A. Hathaway, "Mechanics of Densified Refuse-Derived Fuel," *Proceedings of the Third International Conference on Environmental Problems of the Extractive Industries*, Dayton, Ohio (1977).

the experiments which dealt with storing and handling DRDF. Very little scientific work has been done in this area. That which has been accomplished has demonstrated the differences in the flow properties of DRDF and coal and has indicated that there are procedures to quantitatively determine optimal coal design for a given fuel and DRDF at a given location. The investigation on the use of DRDF similarly found that there are adequate procedures for establishing scientific hypotheses for testing the use of DRDF in furnaces and boilers. However, among all DRDF tests conducted, there is little evidence that these procedures have been followed. The reason for this shortcoming can only be speculated upon. It is possibly a lack of resources to conduct experiments which touch upon a wide variety of engineering disciplines. As indicated earlier, there is very little scientific knowledge about the production of DRDF. There is even less scientific knowledge and operating experience concerning the use of DRDF in military-scale heating and power plants.

5 CONTROL AND DISPOSAL OF BYPRODUCTS FROM DRDF PRODUCTION AND USE

SCS Engineers of Long Beach, CA, were contracted by CERL to search and review pertinent literature regarding the problems encountered with the control and disposal of byproducts from DRDF production and use. The scope of their study was to include also the production and use of fluff refuse-derived fuel which could potentially be pelletized to provide DRDF. The main portion of the SCS study is included in the Appendix; its essential findings are summarized below.[124]

The SCS study indicated that the composition of refuse-derived fuel and its byproducts depends on the composition of the raw solid waste and the type and extent of processing. SCS found that a greater degree of processing generally results in fewer combustion byproducts, but more production byproducts. The trade-offs available between control and disposal of these byproducts have not been quantified.

SCS found that the principal air pollutant resulting from refuse-derived fuel production is process dust from shredding and air classifying operations. They recommend research to more fully characterize the dust's physical, chemical, and biological nature. SCS also recommends that research be directed at the control of solid waste process dust. Conventional air cleaning and protected equipment can probably be adapted for this purpose. However, more definitive particle size data must be gathered for use in designing in-plant dust collection equipment. According to SCS, this dust is primarily organic, and hence can and should be recycled into the refuse-derived fuel feedstock or routed to the boiler itself. Control of the dust should restrict respirable, airborne, and microbial emissions from a processing plant. The SCS study finds that testing must be conducted to determine the levels of volatile organic compounds (acetone, benzene, ether, alcohol, turpentine) emitted during waste processing. Very little of the literature contained quantitative data regarding the levels of volatile organic compounds emitted and the nature of process dust emitted during solid waste processing unit operations.

The SCS study further found that the principal source of liquid byproducts during solid waste processing is equipment washing and runoff from tipping floors. Such wastewaters were found to contain high levels of suspended solids and organic matter and should be treated before being discharged into any receiving water other than a sanitary sewer. According to SCS, conventional wastewater treatment technologies (sedimentation, biological treatment, disinfection) should be sufficient.

The solid wastes generated during refuse-derived fuel production are entirely process waste byproducts. These include ferrous metals, aluminum, glass, rocks, dirt, plastics, rubber, wood, and putrescible yard and food wastes. Of these, some of the materials such as ferrous metals, aluminum, and glass are recoverable with add-on technologies. The remainder can be landfilled in much the same manner as municipal solid waste. Nevertheless, the leachate and gas production potential of solid waste from which combustibles, metal, and glass have been removed should be defined.

With respect to the use of DRDF, SCS found that nitrogen oxides, hydrocarbons, and carbon monoxide emissions from refuse-derived fuel combustion are typically equal to or less than the same emissions from coal combustion. Moreover, sulfur oxide emissions from refuse-derived fuel combustion are less than those produced from burning most coals. On the other hand, chloride emissions from refuse-derived fuel combustion

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[124] J. Marsh, B. West, and J. Woodyard, *Control and Disposal of Byproducts of Refuse-Derived Fuel Production and Use* (SCS Engineers, 1979).

exceed those from coal combustion, but nevertheless are not considered an environmental or public health hazard requiring control. Flyash emissions from refuse-derived fuel combustion generally exceed those from coal combustion, but they can probably be readily controlled by conventional air pollution control technology, such as electostatic precipitators and fabric filters. However, the SCS study found no reported research pertaining to the particle size and particle characteristics of emitted flyash from refuse-derived fuel. Accordingly, the SCS study recommends that research be conducted in this area.

The principal liquid byproduct of refuse-derived fuel combustion is sluice, pond, and ash quench effluent. The effluent quality is such that only treatment for suspended solids removal (by sedimentation) and sometimes organic matter removal (biological treatment) should be necessary.

Finally, the SCS study found that the principal solid byproducts from refuse-derived fuel combustion are bottom ash and flyash. Such ash is generally similar to coal ash, but lower in aluminum and higher in lime, sodium oxide, and several trace elements. Research is recommended to determine how refuse-derived fuel and coal ash differ in terms of both environmental impact from disposal and refuse potential.

6 CONCLUSIONS

There is no mutually satisfactory and generally agreed upon definition of refuse-derived fuel in the solid waste processing and resource-recovery industry. Current definitions either include or exclude solid, liquid, and gaseous fuels derived from the mechanical and/or thermochemical processing of solid waste. As a fuel, refuse-derived fuel exhibits a wide variety of properties, probably because of many different factors such as geographic differences in the nature of solid waste generated, climate, and cultural differences. Nevertheless, there are no standard analytical procedures for determining the critical fuel properties of DRDF. This severely impedes progress within the military in implementing DRDF systems and in writing specifications for DRDF procurement.

Current refuse-derived fuel production processes still have many technological problems. Many plants which have unit operations or which produce a fuel product that may have application at military installations show performance characteristics far less than claimed and planned during their conception. The fact that sequenced solid waste processing unit operations at a given location are continually being upgraded or rehabilitated may contribute to the inherent variability of the product fuel. Within the chemical process industries, there are design procedures for many of the unit operations used in solid waste processing; however, their manifestation and actual design is not always apparent. Most currently operating solid waste processing systems do not have monitoring equipment to record data necessary for advancing technology for recovering fuel and other resources from solid waste.

The use of DRDF in military central heating and power plants would necessarily be based on short-term, inconclusive tests conducted on a large variety of marketed products. No test evaluated in this investigation followed the strictures of the scientific method. The fact that industry-wide use of DRDF has been very sparse, experiments have been unscientific, and the product DRDF tested often less than an optimal substitute fuel for the boilers in which it was evaluated indicates that a high degree of risk can be associated with using DRDF in a military central heating and power plant at present. In the total experimental experience with DRDF, the use of this potentially very valuable waste fuel has not been treated in the same manner that traditional fuel substitution problems have been approached successfully in the past. Rather, a "hit or miss" approach has been used, in which materials that are burned have not been specified for the particular boiler being evaluated, but rather simply represent largely unpredictable and chemically unidentifiable output from a given solid waste processing system. The "hit or miss" approach pervades past investigations of entire systems for which DRDF has been considered as a supplement, including delivery, handling, storage, and combustion.

Some degree of confidence can be maintained in dealing with the byproducts from refuse-derived fuel production and from the use of DRDF on any scale, including the military scale. There are effective methods for treating solid, liquid, and gaseous residues emitted during the production and use of DRDF. Nevertheless, the physical and chemical nature of process dust and its associated public health aspects remain to be explored. Moreover, it is anticipated that the costs associated with sophisticated technology needed to remove toxic and hazardous air pollutants (lead, chromium, cadmium, manganese, and other materials)

from stack gases on boilers burning DRDF could be high. Whether control technology will be required for each particulate species depends on guidelines to be issued by the U.S. Environmental Protection Agency.

Finally, review of literature and analysis of DRDF production and use experience and facilities has clearly revealed the multidisciplinary complexities of using such a material as a substitute or supplementary fuel. Based on the findings of this investigation, it is apparent that a long-term, multiyear commitment of both economic resources and personnel with a wide variety of complementary backgrounds is needed to conduct the vital research, development, testing, and evaluation necessary to acquire reliable DRDF systems at military installations.

7 RECOMMENDATIONS

Based on the findings and conclusions of this investigation, it is recommended that the Armed Services initiate a joint, mutually beneficial multiyear commitment of resources, including multidisciplinary personnel, and conduct research, development, testing, and evaluation in those areas of DRDF production and use which are most vital to supporting the design and conduct of a medium-term demonstration using DRDF in a military central heating or power plant. These areas of inquiry include the storage and handling properties of DRDF, the combustion characteristics of DRDF, the combustion characteristics of DRDF and coal mixtures, and the potential environmental consequences of using DRDF.

It is also recommended that the military services establish a set of procedures and design criteria for a well-monitored, medium-term demonstration of DRDF as a substitute and supplement for coal in a military central heating and power plant. It is recommended that this experiment follow the traditional approach toward fuel substitution, which includes quantification of essential coal burning system parameters, establishment of a subsequent set of hypotheses, and performance monitoring during the experiment to verify or reject these hypotheses. It is recommended that the technological developments and innovations with respect to using DRDF in military-scale heating and power plants be rapidly transferred to the public and other Federal agencies to facilitate the nationwide effort toward conserving conventional nonrenewable fossil fuels.

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Shannon, L. J., D. E. Fiscus, and P. G. Gorman, *St. Louis Refuse Processing Plant: Equipment, Facility, and Environmental Evaluations*, EPA-650/2-75-044/PB 243634 (USEPA-ORD] May 1975).

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METRIC CONVERSION UNITS

Nonmetric Unit	Multiplied by	Yields Metric Unit
MBtu/hr	2.931×10^{-1}	watts (W)
gallon (gal)	3.785	litre (l)
inch (in.)	2.540×10^{1}	mm
ton	9.072×10^{-1}	metric ton (mt)
Btu/lb	2.326×10^{3}	$\frac{\text{joules}}{\text{kilogram}}$ (j/kg)
°F	(°F − 32)/1.8	°C
lb/cu ft	1.602×10^{1}	$\frac{\text{kilogram}}{\text{meter}^3}$ (kg/m^3)
feet (ft)	3.05×10^{-1}	meter (m)
lb	4.54×10^{-1}	kilogram (kg)
mile	1.609	kilometer (km)
hp	9.810×10^{3}	watts (W)
cu yd (yd^3)	7.646×10^{-1}	meter^3 (m^3)
lb/cu yd (lb/yd^3)	4.325×10^{2}	$\frac{\text{kilogram}}{\text{meter}^3}$ (kg/m^3)
acre	4.047×10^{3}	meter^2 (m^2)
sq in (sq in.)	6.452×10^{2}	mm^2
psig (lbf/in.^{2})	1.489×10^{6}	Pascal (Pa)

APPENDIX: CONTROL AND DISPOSAL OF BY-PRODUCTS

General

Both the production and combustion of RDF produce residuals which must be controlled and/or disposed of properly. Selection of the most environmentally sound control and disposal options depends on the nature of these by-products. Considerable effort has been expended to characterize the by-products, but little research has been devoted to the environmental effects of these by-products. Whether such research would be justified or not is partly dependent on whether RDF by-products differ significantly from other wastes and by-products for which adequate control and disposal methods have been developed.

The following discussion of by-products will first address those generated during production and combustion, and second, those generated by various control options (e.g., scrubber sludges, dust from collection equipment, etc.). As much as possible, these by-products will be compared or contrasted to other wastes resulting from conventional fuel use.

RDF Production By-Products

Air Emissions

Processing of municipal solid waste to produce RDF includes several operations, such as shredding and air classifying, which generate dusts.[125] The amount of dust will vary depending on waste characteristics (e.g., moisture content[126]) and the particular processing and auxiliary equipment. For instance, use of a water mist sprayer in a shredder will inhibit associated dust emissions.[127]

At the St. Louis resource recovery plant, dust emission rates have been measured for the shredder (hammermill) and the air classifier.[128] Dust emission rates for the shredder ranged from 0.018 to 0.2 lb/hr. Emissions from the air classifier ranged from 19.9 to 68.2 lb/hr with an average of 50 lb/hr. This is equivalent to an average of 1.25 lb/ton of refuse processed.

The true health significance of the dust emissions depends on particle size, composition, and concentrations in the air around the plant. Dust particle size determines whether a particular particle can travel into the lungs or not. Particles less than 0.3 μ or greater than 5 μ are considered nonrespirable and thus less hazardous from a public health point of view. Tests at the St. Louis facility indicated that more than 80 percent of the dust particulates are greater than 10 μ.[129] Sampling conducted at another resource recovery facility indicated that, on the average, 88 percent of the dust particulates were nonrespirable (Table A1).[130] Thus, the emission rates and concentrations in the

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[125] R. Holloway, "Comparing the Ames and St. Louis Resource Recovery Projects," *Waste Age*, Vol 9, No. 2 (1978), p 36.

[126] L. F. Diaz, L. Riley, G. Savage, and G. J. Trezek, "Health Aspect Considerations Associated with Resource Recovery," *Compost Science*, Vol 17, No. 3 (1976), p 21.

[127] R. Holloway, "Comparing the Ames and St. Louis Resource Recovery Projects."

[128] J. D. Kilgore, L. J. Shannon, and P. G. Gorman, "Emissions and Energy Conversion from Refuse Processing and Mixed Fuel Boiler Firing," *Conversion of Refuse to Energy, Proceedings of the First International Conference and Technical Exhibition* (Institute of Electrical and Electronics Engineers, November 1975), p 1.

[129] J. D. Kilgore, L. J. Shannon, and P. G. Gorman, "Emissions and Energy Conversion from Refuse Processing and Mixed Fuel Boiler Firing," *Conversion of Refuse to Energy, Proceedings of the First International Conference and Technical Exhibition* (November 1975), p 2.

[130] E. J. Duckett, *Physical/Chemical Analyses of Dusts at the Equipment Test and Evaluation Facility*, TR 78-1 (National Council for Resource Recovery, Inc. [NCRR], March 1978), p 13.

Table A1
Particle Size Statistics and Dust Concentrations for Operating Mode

(From E. J. Duckett, *Physical/Chemical Analyses of Dusts at the Equipment Test and Evaluation Facility*, TR 78-1 [NCRR, 1978]. Reprinted with permission.)

	Site* Date	a 4/25	a 4/26	a 5/2	b 4/25	b 4/26	b 5/2	c 4/25	c 5/2	c 5/3	Overall Average
Conc.	Total	22.32	54.38	39.74	19.24	11.07	10.83	49.72	18.78	30.07	28.12
mg/m^3	Resp.	6.34	2.88	2.70	3.12	1.19	3.06	5.07	4.06	2.36	3.42
	Nonresp.	15.98	51.50	32.04	16.12	9.88	7.77	44.65	14.02	27.71	24.70

*Site Code: a = shredder, b = aluminum magnet, c = DRDF room.

plant air alone are not indicative of the health hazard present.

There has been only limited research to characterize the dust emissions inside a resource recovery plant. The cursory analyses performed to date indicate that the dusts are 50 to 70 percent organic with the inorganic fraction composed largely of silicon, aluminum, and calcium (typical of pulverized coal).[131] Tests for asbestos have been negative, but the sampling and analysis procedures used render these results inconclusive. The chemical character of these dusts is still largely speculative.

There has been little evaluation of atmospheric dust levels beyond the immediate plant environs. One study indicated that levels exceeded ambient levels at a distance of 490 ft downwind from the plant.[132] Neither this study nor any of the others cited thus far were performed at full-scale facilities with adequate dust control systems. Most of the plants were pilot or demonstration facilities. There is evidence that conventional air cleaning equipment (e.g., baghouses, masks) will reduce dust concentrations by up to 99 percent.[133] Thus, personal respirators for plant operating personnel and conventional air pollution control equipment should eliminate any environmental problems due to dust emissions.

Another aspect of air emissions related to dust is microbial emissions. Municipal solid waste is high in microorganisms, including fecal bacteria, viruses, and pathogens. Research at the Ames, Iowa, resource recovery facility found airborne bacteria counts in the plant of 1000 to 1,000,000/m^3 compared to 100/m^3 in the ambient air.[134] Approximately 5 percent of these organisms were pathogenic.

Tables A2 and A3 present the results of a study conducted at the NCRR test facility.[135] This study indicated that most of the bacteria (>90 percent of the fecal coliform) were associated with the nonrespirable fraction of the dust emissions. This indicates that ingestion rather than inhalation would be the major route of entry. Since bacteria travel primarily with dust, control of the dust (already discussed) should control microbial emissions.[136]

The volatile organic emissions have not been addressed by any study to date. The role of volatile organics (e.g., acetone, benzene, toluene, turpentine from paint thinners) in causing explosions and fires in shredders has been demonstrated.[137] Since such compounds occur in significant quantities in solid wastes, there is also potential for volatilization to the air. Solvent odors, if any, have probably been masked by typical "garbage odors," and there has been no testing to detect the presence of such hazardous organics.

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[131] Duckett, p 25.

[132] M. L. Renard, *Refuse-Derived Fuel (RDF) and Densified Refuse-Derived Fuel (d-RDF)* (NCRR, June 1978), p 11.

[133] H. Freeman, "Pollutants from Waste-to-Energy Conversion Systems," *Environmental Science and Technology*, Vol 12, No. 12 (1978), p 1254.

[134] D. M. Doran, *Energy from a Wasted Resource: The Ames Experience* (City of Ames, Iowa, 1978), p 30.

[135] E. J. Duckett, *Microbiological Analyses of Dusts at the Equipment Test and Evaluation Facility*, TR 78-2 (NCRR, March 1978), p 20.

[136] Doran, p 30.

[137] R. G. Zalosh, S. A. Wiener, and J. L. Buckley, *Assessment of Explosion Hazards in Refuse Shredders*, ERDA-76-71 (U.S. Energy Research and Development Administration [ERDA], June 1976).

Table A2
Average Concentration of Total Aerobes by Sampling Site and Size Range*

(From E. J. Duckett, *Microbiological Analyses of Dusts at the Equipment Test and Evaluation Facility*, TR 78-2 [NCRR, 1978]. Reprinted with permission.)

		Sampling Site a	Sampling Site b	Sampling Site c	Average Overall
Nonoperating	Total	239	318	315	290
	Respirable	152	195	110	152
	Nonrespirable	87	123	203	138
Operating	Total	>78,200	>24,000	>280,000	>127,500
	Respirable	28,200	4,000	130,000	54,000
	Nonrespirable	>50,000	>20,000	>150,000	> 73,500

*All concentrations are expressed as number of organisms/cu ft air. The concentrations shown are not likely to be typical of a full scale resource recovery facility.

Table A3
Average Concentration of Fecal Streptococci and Fecal Coliforms by Sampling Site and Size Range*

(From E. J. Duckett, *Microbiological Analyses of Dust at the Equipment Test and Evaluation Facility*, TR 78-2 [NCRR, 1978]. Reprinted with permission.)

		Sampling Site a		Sampling Site b		Sampling Site c		Average Overall	
		FS†	FC†	FS	FC	FS	FC	FS	FC
Nonoperating	Total	2	0	3	1	1	1	4	1
	Respirable	1	0	2	0	0	0	1	0
	Nonrespirable	1	0	1	1	6	1	3	1
Operating+	Total	477	220	331	12	1850	501	886	244
	Respirable	82	110	111	1	650	1	281	38
	Nonrespirable	395	110	220	11	1200	500	605	206

*All concentrations are expressed at number of organisms/cu ft air as determined by MPN estimates.

+The concentrations shown are not likely to be typical of a full-scale resource-recovery facility.

†FS = Fecal Streptococci; FC = Fecal Coliforms

Liquid Wastes

There are few sources of liquid wastes from an RDF production facility. In general, the only effluents typical of virtually all such facilities would be runoff from transfer stations and truck aprons and washdown water from equipment washing.

The St. Louis plant is the only facility to have characterized its washwaters to any extent.[138] At this plant the asphalted area around the plant was washed periodically to remove litter and process dust; the refuse receiving area floor is swept rather than washed.[139] A single washdown used about 35 gal/min or a total of 2000 gal. This procedure is repeated twice weekly. Table A4 compares the quality of the raw water and the washdown runoff. As might be expected, the most significant increases are in suspended solids and organic matter. The wastewater should be amenable to conven-

[138] L. J. Shannon, D. E. Fiscus, and P. G. Gorman, *St. Louis Refuse Processing Plant: Equipment, Facility, and Environmental Evaluations*, EPA-650/2-75-044/PB 243634 (U.S. Environmental Protection Agency Office of Research and Development [EPA ORD], May 1975), p 65.

[139] D. E. Fiscus, P. G. Gorman, J. D. Kilgore, "Refuse Processing Plant Equipment, Facilities, and Environmental Considerations at St. Louis Union Electric Refuse Fuel Project," *Proceedings of 1976 National Waste Processing Conference* (American Society of Mechanical Engineers, 1976), p 382.

Table A4
Washdown Water Quality

(From L. J. Shannon, D. E. Fiscus, and P. G. Gorman, *St. Louis Refuse Processing Plant: Equipment, Facility, and Environmental Evaluations*, EPA-650/2-75-044/PB 243634 (EPA ORD, 1975).

Constituent	Raw Water	Washdown Runoff
Total suspended solids (mg/ℓ)	8	6024-9292
Total dissolved solids (mg/ℓ)	248-252	444-564
BOD (mg/ℓ)	none detected	374-765
COD (mg/ℓ)	33.4-52.9	1532-2137
pH	9.5-9.7	6.3-6.5
Total alkalinity (mg/ℓ)	32-62	38-80
Total organic carbon (mg/ℓ)	4.5-6.5	1150-1760

tional wastewater treatment systems (sedimentation/clarification, biological treatment, disinfection).[140]

While St. Louis data does not indicate the use of any detergent or disinfectant, these contaminants may be present in some wash waters. In general, most detergents and soaps are readily amenable to biological treatment. The presence of a disinfectant may not be a problem, as the wastewater could require disinfection. If refractory detergents, deodorants or disinfectants become a problem, carbon absorption is the simplest form of treatment for removing such.

Solid Wastes

There are basically three types of solid wastes generated by RDF production facilities—process by-products, solids from dust collection systems, and wastewater treatment solids. Since there have been no full-scale waste treatment facilities in operation at RDF plants, there is no information (quantitative or qualitative) on the resulting wastewater treatment solids. Considering the relatively small volume of wastewater, the wastewater is typically sent to a large facility handling domestic or industrial wastes.

In some cases, simple pretreatment (e.g., sedimentation) might be required before the waste could be discharged to existing sewers. This would produce a sludge which might be dried and recycled into the plant, mixed with other solid wastes for disposal, or possibly used as a soil amendment, depending on its characteristics. In the event that the wastewater must be discharged to a stream or river, the plant might be required to operate a small, conventional biological treatment plant. This option would produce a sludge similar in many respects to domestic wastewater sludges. Further study of the sludge composition would be required before disposal options could be recommended, however.

Since the facilities currently in operation do not use dust control devices, collected dust does not present a disposal problem. In the future, however, such controls will be a standard feature on full-scale plants. Since the dust has not been collected for disposal thus far, there is no information on its environmental consequences. Given the high organic content of the dust (50 to 70 percent) it might be possible to add it to the refuse at some point in the RDF process, particularly **after** the shredding operations.

Since RDF is made from the combustible fraction of municipal solid waste, 15 to 35 percent of the original waste can remain (air classifier "heavies") after processing. If ferrous metals are recovered, the quantity of residue can be reduced to 8 to 28 percent. The exact quantity and quality of by-products remaining will depend on the type of waste and the sophistication of the resource recovery operation. Some plants produce not only RDF and ferrous metals, but also aluminum and glass aggregate.[141] This leaves only rock, dirt, plastics and rubber, wood, and putrescible yard and food wastes.

Part of the original municipal solid waste disposal problem is thus alleviated through 70 to 90 percent reduction in waste volume. The reduced waste volume

[140] M. L. Renard, *Refuse-Derived Fuel (RDF) and Densified Refuse-Derived Fuel (d-RDF)*, Research Monograph 77-2 (NCRR, June 1978), p 12.

[141] R. L. Chrisman, *Air Classification in Resource Recovery*, RM 78-1 (NCRR, October 1978), p 9.

requires less land for land disposal and could reduce the pollution consequences thereof.[142] The environmental impacts are uncertain, however, because there has been no testing to determine the leachate and gas production potential of this altered waste. The reduced organic content should reduce methane production and the acidity and organic content of the leachate. Otherwise it is difficult to predict leachate quality.

By-Products of RDF Use

General

As with every other aspect of RDF production and use discussed thus far, the quantity and quality of by-products and, by inference, their environmental impact, can vary considerably, depending on the composition of the RDF, the type of emission controls, the air flow rates in the boiler, the combustion temperature, whether the RDF is fired alone or co-fired with coal or oil, the quality of the coal or oil, and so forth. Fugitive dust emissions can be generated at any point of RDF or DRDF handling, as at receiving hoppers, storage bunkers, or fuel conveyors. Although there have been several studies on wastes from RDF combustion, these are based on relatively few plants and are frequently contradictory or inconclusive. In addition, the testing was done on pilot or demonstration plants, often operating under changing experimental conditions. Consequently, the test results to date and any recommendations based thereon may not be extendable to a full-scale plant. The information on the next few pages must be evaluated with these uncertainties in mind.

Fugitive Dust

As with most solid fuels, physical handling of RDF can cause emission of large quantities of dust. Densified RDF is brittle and can be broken up by conventional coal handling equipment. Fluff and dust RDF have high contents of light dust and their handling can lead to high concentrations of dust in the air. Dust generation is most pronounced at points of RDF delivery (e.g., in typical receiving hopper type coal plant delivery systems), around conveyor systems, and at storage bunkers. These fugitive dust emissions can be an explosion and fire hazard, and in-plant dust controls may be necessary.

One control alternative is to modify or replace existing coal handling systems to make them more amenable to the different handling characteristics of RDF. For instance, spillage from coal belt conveyors might be controllable by resetting rollers and perhaps also changing belt material to provide more working depth for carrying RDF. For plants co-firing coal and RDF, separate storage and feeding systems may be required for the RDF. Fugitive dust around storage bunkers may require water spray (as coal dust often is controlled), ventilation, dust hoods, etc. More research is needed on dust volatility and flammability hazard before the extent of the problem can be fully assessed.

Air Emissions

Most of the RDF combustion emission testing to date has been done for systems where RDF is co-fired with coal. Consequently, the emissions monitored are from both coal and RDF. Estimation of the emissions resulting from RDF combustion alone by simply calculating the difference between coal combustion emissions and measured coal-RDF combustion emissions can be misleading. There appear to be several chemical reactions taking place during and after combustion between RDF and coal combustion products which render this additivity assumption invalid. For instance, some of the tests at the Ames, Iowa, facility have revealed that burning a 1:1 coal/RDF mix can decrease SO_x emissions from burning coal alone by up to 67 percent.[143] Since the sulfur content of the combined fuel was reduced by no more than 50 percent through fuel mixing, the additional decrease in SO_x emissions can only be attributed to complexing of some available sulfur in the ash or combustion by-products.

Similarly, estimation of RDF combustion emissions based on emissions from the incineration of municipal solid waste can be misleading. Municipal wastes intended for disposal by incineration are seldom subjected to the elaborate processing and component separation steps which characterize RDF production. As a result, typical incinerator feed contains waste components not present in RDF (e.g., inorganic and dense organic material), and these components can affect the quality of air emissions significantly.

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[142]National Academy of Sciences, *Mineral Resources and the Environment, Supplementary Report: Resource Recovery from Municipal Solid Wastes* (National Academy of Sciences, 1975), p 63.

[143]J. L. Hall, H. R. Shanks, A. W. Joensen, D. B. VanMeter, and G. A. Severns, "Emission Characteristics of Burning Refuse-Derived Fuel with Coal in Stoker Fired Boilers," presented at the 71st Annual Meeting of the Air Pollution Control Association (June 1978), p 7.

Presentation of the results of emission testing for coal combustion, coal/RDF combustion, and municipal solid waste incineration can, however, give a first approximation of the quality and quantity of emissions which could be expected from RDF combustion. All three types of emissions will be presented and compared on the following pages.

Gaseous emissions from RDF combustion include gaseous products of combustion (e.g., CO, SO_x, NO_x, HCl), and vapor-state metals and organics (e.g., mercury, vinyl chloride, hydrocarbons). Particulates include fly ash and unburned fuel particles. The gaseous emissions most often monitored in recent RDF research include sulfur oxides (SO_x), nitrogen oxides (NO_x), chlorides, hydrocarbons, carbon monoxide (CO), formaldehyde, and fluoride.

The effects on SO_x emissions of burning RDF with coal have varied from facility to facility and are often contradictory. Early tests at a Union Electric Power Plant in St. Louis showed no discernible difference in SO_x emissions between burning coal and a coal/RDF mixture.[144] Later tests showed some reduction for a 1:1 mix of coal and RDF.[145] As was noted previously, experience at the Ames facility revealed significant decreases in SO_x when RDF was co-fired with coal. In experiments conducted at an EPA combustion test facility in Columbus, Ohio, SO_x emissions from burning 3.2 weight percent (w/o) sulfur coal were 2352 ppm; SO_x emissions from burning 36 w/o refuse with 3.2 w/o sulfur coal were 1210 ppm, or approximately half.[146] Tests at the University of Texas showed greater than 50 percent reductions in SO_2 emissions over that from coal alone.[147] In comparison, incinerator exhaust gases vary from 33 to 162 ppm SO_2.[148] RDF generally has a lower sulfur content than most coals, and the SO_x emissions are consequently significantly lower in most cases. It is further illustrated by the fact that the EPA Standards of Performance for New Stationary Sources do not include standards for sulfur dioxide emissions from solid waste incinerators. The combustion of RDF alone might not require SO_x control, although more tests are needed before this can be determined with certainty.

Nitrogen oxides present in RDF combustion emissions result from both the oxidation of nitrogen compounds in the waste and high temperature oxidation of nitrogen in the combustion air. Since the nitrogen content of municipal solid waste is negligible and RDF burns at lower temperatures than coal, there should be reduced NO_x emissions from a system burning a high percentage of RDF.[149] This is borne out by tests conducted at Ames, St. Louis, and Columbus. Analyses of stack gases at the Ames utility revealed reductions in NO_x of from 3 to 62 percent when RDF was added to the coal feed at 20 and 50 percent.[150] Tests at Columbus showed a 40 percent reduction.[151] Nitrogen oxides are not considered a problem in incinerator stack gases; one test showed a level of 146 ppm.[152]

Carbon monoxide emissions from RDF combustion have not been as extensively monitored as other emissions. Tests at the Columbus facility showed CO emissions from coal and 36 percent refuse/coal of 0.1 and 0.022 percent respectively, a 78 percent decrease due to RDF addition.[153] Testing at the St. Louis plant

[144] J. D. Kilgore, L. J. Shannon, and P. G. Gorman, "Emissions and Energy Conversion from Refuse Processing and Mixed Fuel Boiler Firing," *Conversion of Refuse to Energy, Proceedings of the First International Conference and Technical Exhibition* (November 1975), p 194.

[145] L. J. Shannon and M. P. Schrag, "Environmental Impact of Waste to Energy Systems," *Energy and the Environment, Proceedings of the Fourth National Conference* (American Institute of Chemical Engineers, October 1976), p 188.

[146] D. A. Oberacker, "Processed Municipal Refuse–A Fuel for Small Power Plant Boilers," *News of Environmental Research in Cincinnati* (USEPA, November 15, 1976).

[147] J. W. Jackson and J. O. Ledbetter, "Stack Emissions from Refuse-Derived Fuel Admix to Boiler Coal," *Journal of Environmental Science and Health*, Vol A12, No. 9 (1977), p 471.

[148] K. P. Anath, L. J. Shannon, and M. P. Schrag, *Environmental Assessment of Waste-to-Energy Process; Source Assessment Document*, EPA-600/7-77-09/PB 272646 (U.S. Environmental Protection Agency Industrial Engineering Research Laboratory [USEPA-IERL], August 1977), p 5.

[149] P. N. Cheremisinoff and A. C. Morresi, *Energy from Solid Wastes* (Marcel Dekker, Inc., 1976), p 58.

[150] B. W. Haynes, S. L. Law, and W. J. Campbell, *Metals in the Combustible Fraction of Municipal Solid Waste*, Report of Investigation 8244 (U.S. Department of the Interior, Bureau of Mines, 1977), pp 13-14.

[151] D. A. Oberacker, "Processed Municipal Refuse A Fuel for Small Power Plant Boilers."

[152] K. P. Ananth, L. J. Shannon, and M. P. Schrag, *Environmental Assessment of Waste-to-Energy Process; Source Assessment Document.*

[153] Oberacker.

failed to produce any conclusive evidence regarding changes in the CO emission level.[154] In either case, the presence of CO is usually an indication of improper combustion conditions and is not so much a function of the fuel as it is a reaction of the plant to a change in fuel.

Virtually all text facilities have encountered increased levels of chloride in stack gases when RDF is burned, but there is some disagreement on the magnitude and significance of the increase. Tests at Ames have indicated that chloride emissions can increase by from 354 to 2924 percent when RDF is mixed with coal over coal alone.[155] Tests at Columbus showed a 157 percent increase.[156] U.S. Air Force studies found increases from 50 mg/m^3 for coal alone to 221 mg/m^3 for 2:1 RDF/coal mix, a 342 percent increase.[157] On the other hand, tests at St. Louis resulted in only moderate increases in chloride, on the order of 17 percent.[158] It is apparent that the chloride content of the stack gas will be dependent on waste characteristics, the operating characteristics of RDF production process employed, and the level of chloride in the coal itself. EPA researchers feel that the chloride levels in question, while contributing to increased equipment corrosion, do not present a significant hazard to human health or the environment.[159]

Hydrocarbon (C_1-C_5) levels in stack gases are more often a function of combustion conditions than the hydrocarbon content of the fuels. Consequently, HC emission levels can vary considerably. Results from the Ames facility do not reveal any significant difference in HC emissions between coal and coal/RDF combustion.[160] Emissions analyses at the EPA test facility in Columbus show a slight increase in HC levels from RDF addition.[161] U.S. Air Force tests show a consistent decrease in HC emissions from facilities burning RDF and coal compared to original coal firing.[162] Based on these results, it seems unlikely that hydrocarbon emissions from properly operated boilers burning RDF or RDF/coal would be a significant problem.

Formaldehyde and fluoride can both be classified, in general, as trace emissions. Formaldehyde is formed during the combustion of cellulose and coal and as a result can vary widely in emissions from coal and RDF firing. Tests at Ames showed that formaldehyde emissions from coal/RDF combustion ranged from a 94 percent decrease to a 2050 percent increase over coal emissions alone. There are presently no standards for formaldehyde emissions from combustion sources.

U.S. Air Force tests have revealed that fluoride emissions from RDF combustion are significantly greater than from coal combustion, with fluoride emission test results of 3.3 mg/m^3 and 0.4 mg/m^3 for a 2:1 RDF/coal mix and 100 percent coal feeds, respectively.[163]

Based on the results of these studies, neither sulfur oxide nor nitrogen oxide emissions from RDF combustion represent any particular hazard. Hydrocarbon and carbon monoxide emissions can be controlled by ad-

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[154] P. G. Gorman, M. P. Schrag, L. J. Shannon, and D. E. Fiscus, *St. Louis Demonstration Final Report: Power Plant Equipment, Facilities, and Environmental Evaluations* EPA-600/2-77-155 B (U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory [USEPA-MERL], December 1979), p 6.

[155] J. L. Hall, H. R. Shanks, A. W. Joensen, D. B. VanMeter, and G. A. Severns, "Emission Characteristics of Burning Refuse-Derived Fuel with Coal in Stoker Fired Boilers," presented at the 71st Annual Meeting of the Air Pollution Control Association (June 1978), pp 13-14.

[156] D. A. Oberacker, "Processed Municipal Refuse—A Fuel for Small Power Plant Boilers," *News of Environmental Research in Cincinnati* (USEPA, November 15, 1976).

[157] J. W. Jackson, *A Bioenvironmental Study of Emissions from Refuse-Derived Fuel*, Report No. 76 M-2/ADA024661 (U.S. Air Force Environmental Health Laboratory, January 1976), p 13.

[158] J. D. Kilgore, L. J. Shannon, and P. G. Gorman, "Emissions and Energy Conversion from Refuse Processing and Mixed Fuel Boiler Firing," *Conversion of Refuse to Energy, Proceedings of the First International Conference and Technical Exhibition* (November 1975), p 194.

[159] H. Freeman, "Pollutants from Waste-to-Energy Conversion Systems," *Environmental Science and Technology*, Vol 12, No. 12 (197?), p 1254.

[160] J. L. Hall, H. R. Shanks, A. W. Joensen, D. B. VanMeter, and G. A. Severns, "Emission Characteristics of Burning Refuse Derived Fuel with Coal in Stoker Fired Boilers," presented at the 71st Annual Meeting of the Air Pollution Control Association (June 1978), pp 13-14.

[161] D. A. Oberacker, "Processed Municipal Refuse—A Fuel for Small Power Plant Boilers," *News of Environmental Research in Cincinnati* (USEPA, November 15, 1976).

[162] J. W. Jackson and J. O. Ledbetter, "Stack Emissions from Refuse-Derived Fuel Admix to Boiler Coal," *Journal of Environmental Science and Health*, Vol A12, No. 9 (1977), p 471.

[163] J. W. Jackson, *A Bioenvironmental Study of Emissions from Refuse-Derived Fuel*, Report No. 76 M-2/ADA024661 (U.S. Air Force Environmental Health Laboratory, January 1976), p 13.

justing boiler operating conditions. Formaldehyde emissions do not differ significantly from coal formaldehyde emissions and should require no special control. Chloride and fluoride emissions from RDF combustion exceed those from coal, but the EPA does not consider either hazardous at present.[164]

Based on the relative ash contents of RDF and coal, particulate (fly ash) emissions can be expected to be higher from RDF than from coal. In general, this is true, although a survey of particulate emission rates reveals that coal/RDF emissions can range from 57 percent below to 116 percent above those from coal burning for similar boiler configurations. Since both coals and RDF can vary widely in ash content depending on source and level of processing, these results are not too surprising, but they make estimation of RDF particulate emission rate difficult. Regardless of the actual rate, RDF combustion does produce a significant amount of fly ash which must be controlled. Both fossil fuel combustion and incineration standards have particulate control guidelines.

In terms of ash quality, it is perhaps even more important to control the particulate fraction from RDF combustion than that from coal combustion. Particulate analyses from the St. Louis coal/RDF co-firing experiments and analyses of incinerator fly ash indicate that RDF fly ash is enriched over coal fly ash in terms of lead, zinc, chromium, antimony, arsenic, barium, cadmium, and mercury, all of which are hazardous to human health.

These chemical differences do not affect the various control options for particulate control, but they do emphasize the necessary for efficient particulate removal. There are basically three control options electrostatic precipitators, fabric filters, and wet scrubbers. The efficiencies for these methods are 80 to 99.5 percent, 95 to 99.9 percent, and 75 to 99 percent, respectively.[165] One researcher has suggested that electrostatic precipitators present an explosion hazard when used for RDF fly ash because of the relatively high carbon content of the ash.[166] However, both the Ames and St. Louis utilities burning RDF use electrostatic precipitators and have experienced no problems. Removal efficiencies have been sufficient to meet current emission standards.

Liquid Wastes

There are essentially three sources of liquid byproducts from the RDF combustion process: ash sluice water, ash quench water, and scrubber water. In general, sluice water and ash quench water have comparable characteristics, and no distinction will be made between them in this report. Scrubber water can refer to the effluent from either particulate scrubbers or gas scrubbers.

During combustion, bottom ash and slag generally fall into an ash pit below the boiler, from which they are flushed to a nearby sluice pond.[167] Frequently, ash quench water and other liquid wastes are also added to the ash pond.

Table A5 presents typical analytical results for sluice water, coal/RDF ash pond effluent, and coal ash pond effluent.

Two observations can be made from this table. Coal/RDF ash pond effluent does not differ appreciably from coal ash pond effluent, and neither are particularly poor in quality as judged by typical surface water supplies or drinking water guidelines. The only significant differences between the two types of ash pond effluents are the organic content and associated oxygen demand. The organic content is not normally a direct threat to public health, but it can affect receiving water quality. Whether the organic content of RDF ash pond effluent is high enough to require any special treatment will depend on the nature and quality of the receiving water. If the effluent is discharged into a sanitary sewer system, the organics will probably

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[164] H. Freeman, "Pollutants from Waste-to-Energy Conversion Systems," *Environmental Science and Technology*, Vol 12, No. 12 (1978), p 1254.

[165] R. A. Olexsey and G. L. Huffman, "Pollution Abatement for Waste-as-Fuel Processes," *Energy/Environment II, Proceedings Second National Conference on the Interagency R&D Program*, EPA-600-9-77-025/PB 277917 (USEPA, November 1977), p 86.

[166] H. G. Rigo, S. A. Hathaway, and F. C. Hildebrand, "Preparation and Use of Refuse Derived Fuels in Industrial Scale Applications," *Conversion of Refuse to Energy, Proceedings of the First International Conference and Technical Exhibition* (November 1975), p 27.

[167] D. E. Fiscus, P. G. Gorman, and J. D. Kilgore, "Bottom Ash Generation in a Coal Fired Power Plant when Refuse-Derived Supplementary Fuel is Used," *Proceedings of 1976 National Waste Processing Conference* (American Society of Mechanical Engineers, 1976), p 481.

Table A5
Levels of Contaminants in Ash Pond Effluents

Contaminant	Coal + RDF Ash* Sluice Water	Coal + RDF Ash* Pond Effluent	Coal Ash* Pond Effluent	Typical+ Fresh Surface Waters	Drinking† Water Guidelines
pH	7.28-9.27	7.2-7.63	8.16-8.4		
BOD (mg/ℓ)	105-200	50-100	<10		
COD (mg/ℓ)	20-960	60	<20		
Dissolved solids (mg/ℓ)	276-840	370-500	347-400		
Alkalinity (mg/ℓ)	144	178	122		
Total organic carbon (mg/ℓ)	50-375	35	<10		
Oil and grease (mg/ℓ)	30-50	10	5		
Phenol (μg/ℓ)	<100	<25	<25		
Nitrate (mg/ℓ)	<12	10	<10		10
Phosphate (mg/ℓ)	1.5	0.5	0.5		
Sulfate (mg/ℓ)	110	125	140		
Chloride (mg/ℓ)	30-59	25	25		
Fluoride (μg/ℓ)	40-400	400	350	<300	
Aluminum (μg/ℓ)	175-3500	100-500	100-500		
Antimony (μg/ℓ)	<4	<4	<4		
Arsenic (μg/ℓ)	20	20	20	10-1000	50
Barium (μg/ℓ)	250	200-250	250	<1000	1000
Beryllium (μg/ℓ)	<20	<10	<10	<1.2	
Boron (μg/ℓ)	150	<100	<100		
Cadmium (μg/ℓ)	<10	<10	<10	<10	10
Calcium (mg/ℓ)	60	80	60		
Chromium (μg/ℓ)	20	20	20	10	50
Cobalt (μg/ℓ)	50	50	50	<10	
Copper (μg/ℓ)	20	15	15	1-280	1000
Iron (μg/ℓ)	100-5000	150-550	50-250		
Lead (μg/ℓ)	50	50	50	23	50
Manganese (μg/ℓ)	50	300	100	1300	
Mercury (μg/ℓ)	5	2	5	0.1-10	2
Molybdenum (μg/ℓ)	75	75	75	100	
Nickel (μg/ℓ)	30-40	10-25	10-25	100	
Selenium (μg/ℓ)	60	50	50	10	10
Silver (μg/ℓ)	10	10	10	50	50
Vanadium (μg/ℓ)	50	50	50	2-300	
Zinc (μg/ℓ)	50-290	30-40	20-30	2000	5000

*These values taken from:

P. N. Cheremisinoff and A. C. Morresi, *Energy from Solid Wastes* (Marcel Dekker, Inc., New York, 1976).

P. G. Gorman, et al., *St. Louis Demonstration Final Report: Power Plant Equipment, Facilities, and Environmental Evaluations*, EPA-600/2-77-155B (USEPA-MERL, December 1977).

J. D. Kilgore, et al., "Emissions and Energy Conversion from Refuse Processing and Mixed Fuel Boiler Firing, *Conversion of Refuse to Energy, Proceedings of the First International Conference and Technical Exhibition* (November 1975).

+National Research Council, *Summary Report: Drinking Water and Health* (National Academy of Sciences, 1977).

†"National Interim Primary Drinking Water Regulations and USPHS Guidelines," National Research Council, *Summary Report: Drinking Water and Health* (National Academy of Sciences, 1977).

create no problem. If the effluent is discharged into a well-aerated, relatively nutrient-poor receiving water, special treatment to reduce the organic loading may not be necessary. In other types of receiving water, RDF ash pond effluent disposal may contribute to dissolved oxygen depletion and stagnation.

If treatment is required to reduce the level of organics before discharge, simple biological processes (e.g., trickling filter, aeration, etc.) will be sufficient in most instances. Should biological treatment be unnecessary, RDF ash pond effluent can be handled in a manner similar to coal ash pond effluent.

AD-A082 773 CONSTRUCTION ENGINEERING RESEARCH LAB (ARMY) CHAMPAIGN IL F/G 13/2
PRODUCTION AND USE OF DENSIFIED REFUSE-DERIVED FUEL (DRDF) IN M--ETC(U)
MAR 80 S A HATHAWAY, J S LIN, D L MAHON MIPR-FY8952-78-65012
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Under current effluent limitations guidelines, coal ash pond effluents are limited in three categories—pH (6.0 to 9.0), total suspended solids (100 ml/ℓ for any one day, 30 mg/ℓ average for 30 days), and oil and grease (20 mg/ℓ for any one day, 15 mg/ℓ average for 20 days). According to Table A5, most ash pond effluents can meet the pH and oil and grease guidelines with no further treatment. Settling tanks and possibly chemical treatment may be necessary to meet the suspended solids guidelines.

Ash pond discharges may be subject to various state and/or local effluent limits. Since most of the trace constituents of ash pond effluents are within drinking water limits, this will generally impose no further treatment burden. The exact requirements and treatments necessary must be determined for each case.

Burning RDF in a power plant boiler destroys most of the microorganisms present in the RDF. Consequently, sluice water from RDF or coal/RDF combustion poses no more of a problem in terms of bacteria than when coal is burned.[168]

Solid By-Products

There are several potential solid by-products generated from RDF combustion: fly ash, slag and bottom ash, scrubber sludges, and wastewater treatment sludges. Since RDF combustion will reduce SO_2 emissions from a coal-fired boiler, flue gas desulfurization (FGD) sludge generation will also decrease in proportion with the SO_2 reduction. Scrubber sludges from coal/RDF combustion would not differ greatly in quality from coal combustion scrubber sludges. Therefore, scrubber sludge disposal is a problem more directly related to coal combustion technology than to RDF combustion. There is a sizeable data base available on the control and disposal of FGD sludges which can be consulted for more detailed information.[169]

The compositions of wastewater (ash pond effluent) treatment sludges will vary depending upon the scope of treatment required. If simple settling is sufficient, the sludge will be comprised mainly of ash and slag with most of the soluble constituents removed. The resulting ash will not differ physically from normal fly ash or bottom ash, and as such should be chemically inert.

Chemical treatment to reduce dissolved solids from ash pond effluent will probably involve the use of lime or alum. The resulting sludge will differ from the settled ash only in higher levels of calcium, aluminum, or sulfate, depending on the treatment chemical used. All are present in ash naturally, however, and consequently present no new problems in control or disposal other than mechanical problems of dewatering or handling.

If biological treatment is necessary to remove organics from ash pond effluent, some type of biological sludge will be produced. Biological treatment should follow settling, and the resultant sludge will not contain any significant quantities of suspended ash. On the other hand, the sludge may be enriched with soluble trace elements originating in the settled ash. No research has been conducted to date to characterize the type of biological sludge which would be produced in treating RDF ash pond effluent. Consequently, it can only be postulated at this point as to how disposal of this sludge might differ from the disposal of ordinary biological sludges. Since effluent flow rates and organic concentrations are not high, treatment sludge volumes would be low compared to the quantities of bottom ash and fly ash produced.

Bottom ash and fly ash are the principal solid by-products subject to control and disposal. Co-firing coal and RDF produces marginally greater quantities of fly ash than firing coal alone, and quantities of bottom ash can be increased by factors of 6 to 7, from 1333 lb/hr to 8995 lb/hr.[170] On an equal fuel weight basis, combustion of RDF/coal mixtures can produce 7 to 8 times the fly ash and bottom ash as coal combustion.

RDF generally has a higher ash content than coal. The increase in the bottom ash from RDF combustion can be attributed in part to the presence of noncombustible (e.g., metals, glass, dirt, etc.) and organic

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[168] P. G. Gorman, M. P. Schrag, L. J. Shannon, and D. E. Fiscus, *St. Louis Demonstration Final Report: Power Plant Equipment, Facilities, and Environmental Evaluations*, EPA-600/2-77-155 B/PB 279828 (USEPA-MERL, December 1977), p 73.

[169] D. E. Weaver, C. J. Schmidt, and J. P. Woodyard, *Data Base for Standards/Regulations Development for Land Disposal of Flue Gas Cleaning Sludges*, EPA-600/7-77-118/PB 280135 (USEPA-MERL, December 1977).

[170] P. G. Gorman, M. P. Schrag, L. J. Shannon, and D. E. Fiscus, *St. Louis Demonstration Final Report: Power Plant Equipment, Facilities, and Environmental Evaluations.*

materials which do not receive sufficient resident time for burnout (e.g., leather, rubber, etc.). The amount of bottom ash, slag, and fly ash generated by RDF combustion can therefore be controlled to some extent by the degree of processing to which the RDF is subject.

There have been no studies conducted exclusively on RDF ash to determine environmentally safe disposal options. In most RDF test facilities, the solid wastes are either being stored, buried, or generally commercially handled as part of the coal wastes. Coal ash is usually landfilled, ponded, or recycled. Whether RDF ash should be handled similarly depends on the extent to which RDF ash and coal ash are the same chemically and physically.

There have been no studies addressing the physical nature of RDF ash (e.g., crystalline structure) but there have been some studies of RDF ash chemical characteristics. Table A6 presents a comparison of the chemical composition of coal ash, incinerator ash, and RDF ash. All of the ashes are primarily (90 to 95 percent) iron aluminum silicates enriched with lime (CaO), magnesia (MgO), and alkali oxides (Na_2O, K_2O). RDF ashes tend to be lower in aluminum and higher in lime and sodium oxide than coal ashes, but the major ele-

Table A6
Ash Compositions

Constituent	Coal+	Coal†	Incinerator**	RDF/Coal++	RDF/Coal††	RDF††
SiO_2 (%)	26.7-46.4	*	*	38.8-68.4	*	41.8-54.1
Al_2O_3 (%)	9.5-18.4	22.3-27	17-26.8	4-16.3	8.9	8.4-18.2
Fe_2O_3 (%)	16.5-53.4	8.8-9.1	3.4-12.4	1.4-12.16	9.7	2.9-8.1
TiO_2 (%)	*	1.0-1.2	4.2-7.0	0.28-2.37	0.66	1.1-2.0
P_2O_5 (%)	*	*	*	0.29-2.37	*	0.28-1.25
CaO (%)	4-6.7	5.9-6.6	4.6-12.0	5.8-14.6	11.2	10.4-15.5
MgO (%)	0.59-1.03	2.5-3	0.35-2.0	0.8-2.2	*	1.9-3.2
Na_2O (%)	0.17-1.2	4.3-4.4	1.5-2.6	4.9-10.9	*	3.5-5.2
K_2O (%)	0.86-2.1	1.9-2.2		1.14-7.6	1.76	1.5-2.3
Antimony (ppm)	*	*	139-760	*	*	*
Arsenic (ppm)	*	*	9.4-74	*	*	*
Barium (ppm)	740-1253	2500-2780	1600-3600	*	*	*
Beryllium (ppm)	13-17	12-16	*	*	*	*
Boron (ppm)	123-770	*	*	*	*	*
Cadmium (ppm)	*	1.2-1.85	<5-194	*	*	*
Chromium (ppm)	193-221	113-138	730-1900	*	170	*
Cobalt (ppm)	64-172	36.7-46	25-54	*	*	*
Copper (ppm)	293-379	128-133	300-2000	*	171	*
Lead (ppm)	89-183	70-82	1800-5400	*	6181	*
Manganese (ppm)	170-1432	460-496	2000-8500	*	*	*
Mercury	*	0.13-0.19	*	*	*	*
Nickel (ppm)	154-263	98-109	480-960	*	55	*
Selenium (ppm)	*	*	1.4-13	*	16.8	*
Silver (ppm)	*	<3	52-220	*	*	*
Strontium (ppm)	668-1987	1200-1700	220-1100	*	164	*
Tin (ppm)	32-92	42	1200-2600	*	*	*
Vanadium (ppm)	249-390	*	110-166	*	550	*
Zinc (ppm)	195-310	208-216	7800-26,000	*	6045	*

*Constituent not analyzed for these.

+S. Torrey, ed., *Coal Ash Utilization*, Pollution Technology Review No. 48 (Noyes Data Corporation, Park Ridge, New Jersey, 1978).

†B. W. Haynes, S. L. Law, and W. J. Campbell, *Metals in the Combustible Fraction of Municipal Solid Waste*, Report of Investigations 8244 (U.S. Department of the Interior, Bureau of Mines, 1977).

**R. R. Greenberg, W. H. Zoller, and G. E. Gordon, "Composition and Size Distribution of Particles Released in Refuse Incineration," *Environmental Science and Technology*, Vol 12, No. 5 (May 1978), pp 566-573.

++P. N. Cheremisinoff and A. C. Morresi, *Energy from Solid Wastes* (Marcel Dekker, Inc., New York, 1976).

††J. C. Even, et al., *Evaluation of the Ames Solid Waste Recovery System; Part I–Summary of the Environmental Emissions: Equipment, Facilities, and Economic Evaluations*, EPA-600/2-77-205 (USEPA-MERL, 1977).

ment compositions of RDF ashes are generally within the range of compositions which can be exhibited by coal ashes. The principal differences are in the trace element compositions.

RDF fly ash is generally higher in antimony, arsenic, barium, cadmium, chromium, copper, lead, mercury, silver, and zinc than coal ash.[171] (Some of the values for other elements are higher for incinerator ash than coal ash, but these values are not necessarily representative of RDF ash values due to their removal during processing. For instance, incinerator ash is high in tin, but RDF processes remove tin from the waste).

There have been no studies to determine whether this higher trace element content in RDF ash increases its potential for environmental impact during disposal, particularly whether these elements are any more soluble than in coal ash. In coal fly ash, a majority of trace elements are incorporated into the alumino-silicate crystal lattice where they are considered insoluble. There have been no laboratory studies to determine the solubility of the trace elements in RDF ash.

Proper landfilling of coal does not cause any adverse environmental impact. Most of the leachable constituents (Ca, Fe, Na, K) are naturally present in mineral soils and do not present any appreciable public health or environmental hazard at the levels encountered. Furthermore, in alkaline soils the more hazardous trace elements (Cd, Cr, Pb, Hg, Ag, Zn) tend to precipitate in the soil and are thus immobilized. In general, the same principles should hold true for RDF ash. In particular, the increased alkalinity of RDF ash (from increased quantities of lime, magnesia, and alkali oxides) should lower the overall solubility and mobility of the trace elements.

RDF ash may possess the same physical properties (and thus recycle potential) as coal ash, although this too has not been tested. Coal ash is commonly collected and used as filler in concrete, asphalt, and roofing materials. This both simplifies and complicates the disposal problem. It is simplified in the sense that a safe disposal option–resuse–is available. It is complicated in the sense that there is already a limited market for coal ash. In 1977, only about 21 percent of the total coal ash produced was reused.[172] There seems to be little immediate prospect of increased utilization in the U.S., although the potential does exist in the long term. In 1972, for example, the total utilization of coal ash in Belgium, France, Poland, the United Kingdom, and West Germany exceeded 50 percent.[173] In the future, there may also be a market for minerals extracted from ash.

Summary

One way of looking at the problem of RDF production and use by-products is to develop a mass-balance for an RDF production facility and boiler. This sort of summary presentation can more clearly depict the overall by-product generation potential of RDF than the more detailed discussions in the text. Of course, this mass balance approach is at best general, representing the average or typical system; there can be considerable variation between different resource recovery facilities and boilers. However, mass balance calculations, however approximate, make it more readily possible to conceptualize the full scope of the RDF by-product picture.

Figure 1 in the main text presents a resource recovery/RDF plant mass balance. The refuse composition is based on the national average figures. For the purpose of this calculation, a delivered refuse volume of 1 000 000 kg/mo was selected as being representative of Army installations.[174] Values for dust, dirt and grit, ferrous metals, and wastewater generation were based on operation values from the Ames and St. Louis facilities.[175] The RDF production rate is lower than that experienced at Ames,[176] consistent with NCRR fig-

[171] P. G. Gorman, M. P. Schrag, L. J. Shannon, and D. E. Fiscus, *St. Louis Demonstration Final Report: Power Plant Equipment, Facilities, and Environmental Evaluations*, EPA-600/2-77-155 B (USEPA-MERL, December 1977), pp 4-5.

[172] "Power Plant Ash Disposal a Growing Problem," *Chemical and Engineering News*, Vol 56, No. 45 (1978), p 26.

[173] R. A. Carnes, "Nature and Use of Coal Ash from Utilities," *News of Environmental Research in Cincinnati* (USEPA, June 30, 1975), p 2.

[174] S. A. Hathaway, *Recovery of Energy from Solid Waste at Army Installations*, Technical Manuscript E-118/ADA044814 (CERL, August 1977), p 1.

[175] J. C. Even, S. K. Adams, P. Gheresus, A. W. Joensen, J. L. Hall, E. D. Fiscus, and C. A. Romine, *Evaluation of the Ames Solid Waste Recovery System: Part I–Summary of the Environmental Emissions: Equipment, Facilities, and Economic Evaluations*, EPA-600/2-77-205 (USEPA-MERL, November 1977), p 28; L. J. Shannon, D. E. Fiscus, and P. G. Gorman, *St. Louis Refuse Processing Plant: Equipment, Facility, and Environmental Evaluations*, EPA-650/2-75-044/PB 243634 (USEPA-ORD, May 1975), p 64.

[176] Even, et al., p 28.

ures,[177] and higher than Army estimates;[178] as such, it represents an achievable value.

The values for plant wastewaters reflect only the solids content of the effluent. If any chemical or biological treatment is employed, the production of sludge will increase the solid waste from the wastewater. Generally, this sludge must be disposed of via landfilling.

The process dust can conceivably be cycled into the RDF. Otherwise it too becomes a waste to be landfilled.

The ferrous metals are recovered. Some plants also recover the aluminum and glass included in the heavy rejects category. The remaining heavy rejects are disposed of, usually by landfilling.

Figure A1 presents mass balances for the combustion of RDF and a medium sulfur coal (3 percent sulfur, 12 percent ash). The values in this mass balance are even more approximate than those for the resource recovery plant. Among the factors affecting combustion by-product generation are the fuel characteristics, the type of boiler, combustion temperature, fuel feed and consumption rate, percentage air, and the combustion efficiency. Where possible comparable boilers were chosen to derive the values for this mass balance, but this limits the usefulness of the numbers to a comparison between RDF and coal; the numbers are not necessarily descriptive of actual boilers and should not be interpreted as such. However, they are valuable for comparing coal and RDF fired systems.

The coal and RDF quantities selected represent roughly equivalent heat production, the Btu/lb for coal being approximately twice that of RDF.[179] The RDF produced in Figure A1 was used for this mass balance. This fuel is 8.6 percent inorganic fines, and the com-

[177] M. L. Renard, *Refuse-Derived Fuel (RDF) and Densified Refuse-Derived Fuel (d-RDF)* (NCRR, June 1978), p 14.

[178] Hathaway, *Recovery of Energy from Solid Waste at Army Installations*, p. 6.

[179] J. W. Jackson, *A Bioenvironmental Study of Emissions from Refuse-Derived Fuel*, Report No. 76 M-2/ADA024661 (U.S. Air Force Environmental Health Laboratory, January 1976), p 4.

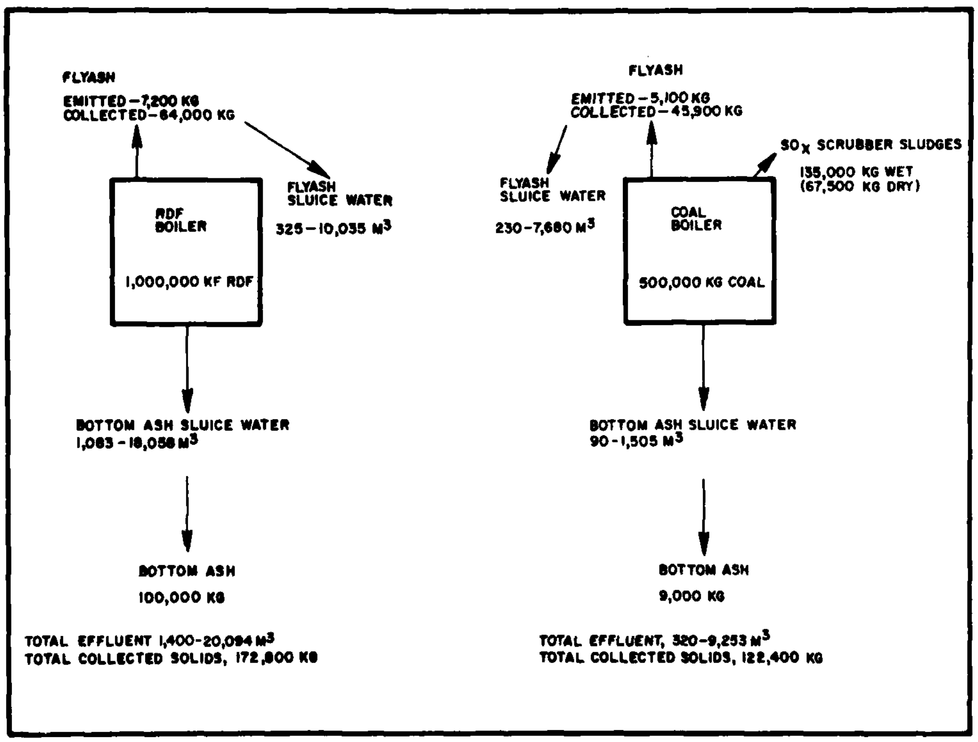

Figure A1. RDF and coal combustion mass balance.

bustible fraction is 10 percent ash for a total ash content of 18 percent. A 12 percent ash, 2 percent sulfur coal was chosen. The division between bottom ash and fly ash was based on average figures from actual operations.[180] A particulate control efficiency of 90 percent was assumed.

No useable figures were available on the quantities of wastewater per unit weight of fuel. The wastewater figures are derived from estimates of water use per weight of ash conveyed.[181]

The only gaseous emission considered in this mass balance was SO_x. RDF, being a low sulfur fuel, was deemed to have insufficient emissions to warrant controls. A lime scrubber of 85 percent efficiency was used to calculate SO_x control sludge quantities from the coal boiler.[182]

This mass balance does not include effluents from cooling towers, equipment cleaning, sanitary wastes, and so forth, as these are considered to be comparable between the two systems. These calculations also do not include wastewater treatment sludges. Since sluice pond effluents from both systems are similar, comparable treatment of both waste streams could produce three to four times as much sludge from RDF effluents as from coal effluents. From the data available, however, wastewater treatment sludge quantities for any particular boiler and fuel cannot be predicted with any accuracy.

There are two ways to view the results of these mass balances. On the one hand, the production and combustion of RDF from 1000000 kg of refuse produces 290032 kg of waste solids and 1148 to 22405 m^3 of wastewater as opposed to 94656 kg and 247 to 7156 m^3 respectively for an equal Btu amount of coal. (Note that these numbers are adjusted to be consistent with Figure 2 and do not match those on Figure A1.) Of course, the numbers for coal do not include coal mining or coal processing either of which could boost the waste and effluent values for coal up to those of RDF. Furthermore, it may be misleading to refer to RDF processing and burning as "producing" waste byproducts. In the mass balance presented here, 1000000 kg of waste solids (municipal refuse) is converted to 69000 kg of reusable iron, 10^{10} Btu, and 290000 kg of waste solids, 60 percent of which is ash with several potential uses. If all the ash could be reused, that original 1000000 kg of waste becomes 117000 kg of waste, an 88 percent reduction.

[180]D. E. Fiscus, P. G. Gorman, and J. D. Kilgore, "Bottom Ash Generation in a Coal Fired Power Plant when Refuse-Derived Supplementary Fuel is Used," *Proceedings of 1976 National Waste Processing Conference* (American Society of Mechanical Engineers, 1976), p 486.

[181]C. R. Nichols, *Development Document for Effluent Limitations Guidelines and New Source Performance Standards for the Steam Electric Power Generating Point Source Category*. EPA-440/1-76/029-a/PB 240853 (USEPA, Office of Water and Hazardous Materials, October 1974), p 151.

[182]N. P. Phillips and R. M. Wells, *Solid Waste Disposal*, EPA-650/2-74-033 (USEPA-ORD, May 1974), p 214.

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